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Analysis of WLTP typical driving conditions that affect non-exhaust particle emissions

Grigoratos Theodoros, Martini Giorgio
and Steven Heinz

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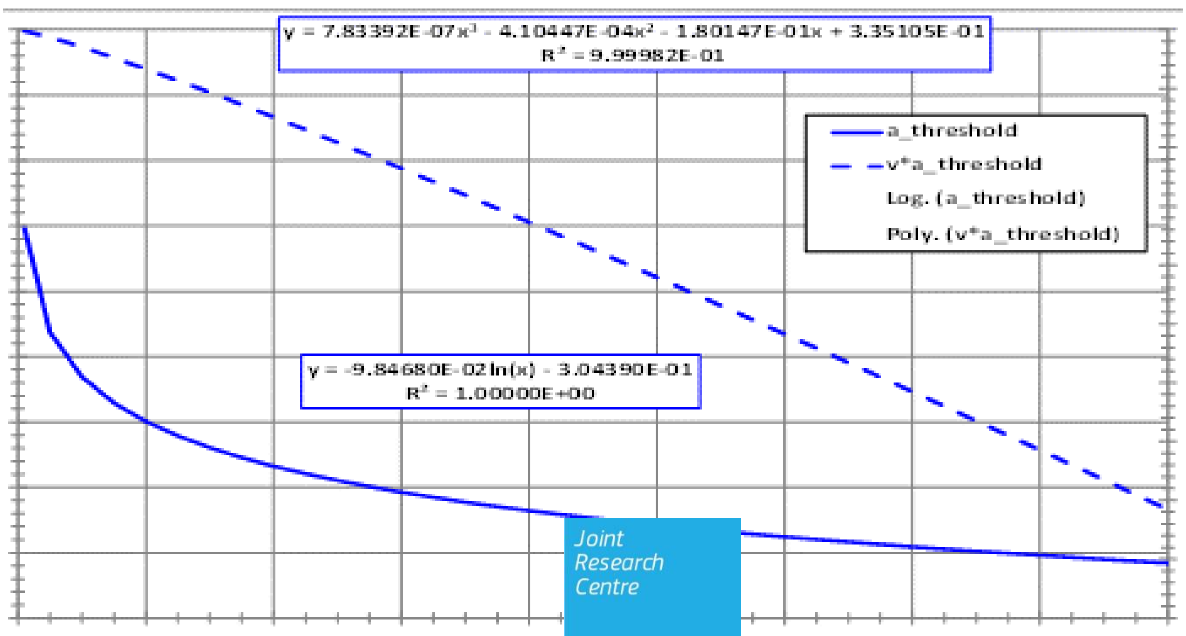

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Foreword

The UNECE Particle Measurement Programme Informal Working Group (PMP IWG), was set up with the objective of developing an alternative metric with increased sensitivity compared to the existing Particulate Matter (PM) mass measurement system for Heavy Duty (HD) and Light Duty (LD). The activity of he group has resulted in the development of a particle number counting methodology and related limit values that are currently included in the Euro5/6 and Euro VI EU Regulations. Recently the PMP IWG has received a new mandate from UNECE Working Party on Pollution And Energy (GRPE) in order to consider whether there is a need to extend particle measurement procedures to additional sources such as brake wear and the interaction between tyres and road.

Acknowledgements

The authors would like to thank all the members of the UNECE Particle Measurement Programme Informal Working Group (PMP IWG) for the valuable inputs to the work presented in this report by contributing to the identification of the most important parameters affecting non-exhaust particle emissions.

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Abstract

Driving conditions have a large influence on particle generation from brake and tyre wear processes. Different driving conditions in experimental investigation of particle emissions from brake and tyre wear is one of the reasons why different - or even sometimes- contradictory conclusions are reported. In order to harmonize future studies on particles from brake and tyre wear and improve the comparability of the relative results, the definition of "normal" or "typical" driving patterns has been identified by PMP group as an important working item.

The proposed approach is to use activity data collected in the framework of other projects in order to investigate typical acceleration / deceleration frequency distributions. The main objectives of this activity are to compare "typical/normal driving conditions" derived by existing datasets like the WLTP vehicle activity database with the industry standards, as well as to reach, if possible, a shared definition of normal, severe, extreme or infrequent conditions. This will narrow down the range of driving conditions to be taken into consideration as far as non-exhaust particle emissions are concerned and will improve the comparability of future studies. This report describes the results of a detailed analysis of the WLTP in-use database. The results are provided in this report and in dedicated ACCESS databases.

1 Introduction

Driving conditions have a large influence on particle generation from brake and tyre wear processes. From the survey of the available literature it appears that different driving conditions in experimental investigation of particle emissions from brake and tyre wear is one of the reasons why different - or even sometimes- contradictory conclusions are reported. In particular, during hard accelerations or decelerations ultrafine particles can be generated due to the high temperatures reached in brakes and tyres. The question is whether these conditions are within the range of the driving conditions that can be considered "normal/typical" or should be considered as "extreme" with a low occurrence frequency.

In addition, there are already standardized test conditions used by the industry in designing brake systems as well as tyres.

In order to harmonize future studies on particles from brake and tyre wear and improve the comparability of the relative results, the definition of "normal" or "typical" driving patterns and in particular of typical accelerations/decelerations has been identified by PMP group as an important working item.

The proposed approach is to use activity data collected in the framework of other projects in order to investigate typical acceleration / deceleration frequency distributions. The main objectives of this activity are to compare "typical/normal driving conditions" derived by existing datasets like the WLTP vehicle activity database with the industry standards, as well as to reach, if possible, a shared definition of normal, severe, extreme or infrequent conditions. This will narrow down the range of driving conditions to be taken into consideration as far as non-exhaust particle emissions are concerned and will improve the comparability of future studies.

This report describes the results of a detailed analysis of the WLTP in-use database. The results are provided in this report and in dedicated ACCESS databases.

2 Description of the WLTP database

The WLTP in-use driving behaviour database consists of driving behaviour data from five different regions in the world (see Table 1). The data from Europe and the major part of the US data is customer data and thus reflects the practical use of the vehicles in real traffic. Data coming from India, Japan and Korea are not customer data. In these countries vehicles, routes and driving times were chosen in order to reflect "representative" driving.

Region	Mileage [km]	Duration [h]	Short Trips [#]
Europe	432,572	8,003	200,813
India	73,694	1,824	17,358
Japan	49,868	1,255	55,944
Korea	32,399	790	26,972
USA	155,160	2,557	65,551
Total	**743,694**	**14,430**	**366,638**

Table 1: Overview of the WLTP in-use driving behaviour database

The European data was collected in Belgium, France, Germany, Italy, Poland, Slovenia, Spain, Sweden and UK. The total number of vehicles used was 146. The US customer data was collected in Atlanta, Denver, Los Angeles, San Diego and San Francisco. The number of vehicle models was 5. Information regarding the technical data of the vehicles is given in Tables A1 to A4 of the Annex.

The data include vehicle speed, engine speed (not for all vehicles), date and time of the day and trip number with a sample rate of 1 Hz. The acceleration was calculated using the following two approaches:

- $a_i = (v_{i+1} - v_i)/3.6$
- $a_i = (v_{i+1} - v_{i-1})/2/3.6$

The second approach was used for the further analysis within the WLTP development work.

The following indicators were assigned to the datasets:

- Trip number,
- Short trip number within a trip (short trip = consecutive datasets with v >= 1 km/h),
- Acceleration (consecutive datasets with a > 0.1389 m/s²),
- Deceleration (consecutive datasets with a < -0.1389 m/s²),
- Cruise (consecutive datasets with - 0.1389 m/s² ≤ a ≤ 0.1389 m/s²).

3 Mileage statistics

The total mileage of the data is almost 800,000 km. 4.7% of the mileage is related to trips below 3000 m. These trips were disregarded for the analysis of acceleration and deceleration distributions. Another 5.8% of the total mileage belongs to trips with faulty sections (jumps in vehicle speed, etc.). This data was also excluded from the analysis. The remaining total mileage is 714,198 km.

4 Overview of results and definition of extreme conditions

Table 2 (a-d) provide an overview of the most important distributions of this analysis split up into different regions and road categories. The US data could not be included in this particular part of the analysis because the available data do not allow the split into different road categories (i.e. urban, rural, motorway). However, US data were treated based on speed categories and the results are provided.

Table 2 provides detailed data regarding the cumulative frequency (from 5th – 95th percentile) of all parameters related to the use of brakes and tyres. Information regarding average vehicle speed, average acceleration and deceleration, duration of acceleration and deceleration, duration of vehicles' stop as well as the brake phase duration, and short trip duration is provided for different regions and road categories.

It can be seen from Table 2a that in European urban areas 95% of average speeds are lower than 60 km/h. Accelerations are rarely higher than 1.3 m/s^2, while decelerations are almost always lower than 1.7 m/s^2. Vehicles stay steel for no longer than 55 s, while the duration of the braking phase rarely exceeds 9.0 s. These conditions could be characterized as the threshold beyond which the driving behaviour for a typical European urban area could be characterized as **"extreme"**. Similar thresholds could be extracted from the 95th percentiles of the two other types of road category (rural and motorway). Accordingly, all parameters that fall in the first 5th percentile shall not be considered when trying to replicate real world driving conditions. Median driving conditions in European urban areas as expressed from the 50th percentile of the distributions include median speed of 28.3 km/h, acceleration of 0.45 m/s^2, deceleration of 0.55 m/s^2 and braking phase duration of 3.3 s. Vehicles stay steel between short trips for approximately 6 s, thus reflecting typical traffic jam conditions with continuous stop and go phases.

Europe	Cum Frequency	Vehicle Speed [km/h]	Acceleration [m/s^2]	Deceleration Duration [s]	Deceleration [m/s^2]	Stop Duration [s]	Short Trip Distance [m]	Brake Phase Duration [s]
Motorway	**5%**	47.4	≤0.20	≤2.0	≤0.20	≤2.0	≤50	1.0
	10%	77.3	≤0.20	≤2.0	0.22	≤2.0	≤50	1.0
	25%	101.2	≤0.20	≤2.0	0.28	2.4	104	1.3
	50%	114.8	0.27	3.5	0.38	6.2	4,290	2.5
	75%	126.0	0.45	6.2	0.56	13.8	22,858	4.6
	90%	132.4	0.74	10.6	0.88	30.2	51,913	7.8
	95%	137.9	0.98	14.6	1.20	48.4	79,094	10.3
Rural	**5%**	14.5	≤0.20	≤2.0	≤0.20	≤2.0	<34	1.0
	10%	25.5	≤0.20	≤2.0	0.23	≤2.0	34	1.0
	25%	44.6	0.20	2.3	0.30	2.3	337	1.9
	50%	64.7	0.35	4.3	0.47	5.9	1,736	3.4
	75%	84.9	0.54	7.8	0.76	18.2	6,836	5.6
	90%	103.7	1.06	12.9	1.29	36.9	15,546	8.3
	95%	113.7	1.31	16.9	1.70	52.0	26,086	10.2
urban	**5%**	1.7	≤0.20	≤2.0	≤0.20	≤2.0	≤50	1.0
	10%	4.6	≤0.20	≤2.0	0.25	≤2.0	≤50	1.0
	25%	14.0	0.25	2.6	0.33	2.3	69	1.9
	50%	28.3	0.45	4.7	0.55	5.8	264	3.3
	75%	42.4	0.79	7.8	0.91	18.5	782	5.2
	90%	53.6	1.16	11.7	1.40	38.6	1,818	7.5
	95%	60.2	1.35	14.5	1.70	55.0	3,270	9.0

Table 2a: Overview of the distributions of parameters related to non-exhaust emissions in Europe

Similarly it can be seen from Tables 2b-d that average speeds in different urban areas in Asia are rarely higher than 56.4-65.2 km/h. Also, accelerations and decelerations higher than of 0.80-1.34 and 1.21-1.48 m/s^2, respectively, as well as braking phase durations higher than 7.9-10.6 s can be characterized as **"extreme"**. When looking into the distributions of the parameters in urban areas in Asia it comes out that all parameters are similar to those recorded in European urban areas except for the lower range of accelerations (~0.8 m/s^2) that are found in India. General differences observed in India can also be attributed to the different types of vehicles (see annex) and roads.

India	Cum Frequency	Vehicle Speed [km/h]	Acceleration [m/s^2]	Deceleration Duration [s]	Deceleration [m/s^2]	Stop Duration [s]	Short Trip Distance [m]	Brake Phase Duration [s]
Motorway	**5%**	9.1	≤0.10	≤2.0	0.11	≤2.0	≤50	1.0
	10%	19.6	≤0.10	≤2.0	0.13	≤2.0	≤50	1.0
	25%	32.8	≤0.10	2.2	0.17	2.1	107	1.5
	50%	55.0	0.15	3.8	0.27	6.2	1,839	2.7
	75%	69.8	0.32	6.7	0.48	17.9	15,894	4.5
	90%	79.4	0.56	10.7	0.86	50.8	42,630	6.9
	95%	83.9	0.74	13.7	1.19	93.1	52,700	8.7
Rural	**5%**	6.2	≤0.10	≤2.0	0.12	≤2.0	≤50	1.0
	10%	11.6	≤0.10	≤2.0	0.13	≤2.0	≤50	1.0
	25%	23.3	≤0.10	2.4	0.18	2.1	233	1.6
	50%	37.0	0.19	4.0	0.30	5.9	2,558	2.8
	75%	50.7	0.38	6.7	0.57	17.3	9,304	4.3
	90%	62.4	0.63	10.1	1.01	57.9	22,050	6.1
	95%	68.7	0.82	12.8	1.36	102.8	35,575	7.6
urban	**5%**	1.7	≤0.10	≤2.0	0.12	<1.9	≤50	1.0
	10%	4.7	≤0.10	≤2.0	0.13	<1.9	≤50	1.0
	25%	13.1	≤0.10	2.3	0.19	1.9	111	1.4
	50%	25.0	0.21	3.9	0.32	6.2	576	2.6
	75%	38.6	0.40	6.8	0.57	21.0	1,620	4.2
	90%	54.1	0.64	10.5	0.94	51.3	4,206	6.4
	95%	65.2	0.80	13.2	1.21	74.0	7,912	7.9

Table 2b: Overview of the distributions of parameters related to non-exhaust emissions in India

Japan	Cum Frequency	Vehicle Speed [km/h]	Acceleration [m/s^2]	Deceleration Duration [s]	Deceleration [m/s^2]	Stop Duration [s]	Short Trip Distance [m]	Brake Phase Duration [s]
Motorway	**5%**	2.1	≤0.10	≤2.0	0.12	≤2.0	≤50	1.0
	10%	5.6	≤0.10	≤2.0	0.13	≤2.0	≤50	1.0
	25%	20.9	≤0.10	≤2.0	0.18	2.8	≤50	1.0
	50%	62.8	0.18	2.0	0.28	6.1	143	1.6
	75%	81.2	0.38	4.1	0.48	15.8	1,097	3.0
	90%	94.0	0.67	7.4	0.77	34.3	11,840	5.6
	95%	99.7	0.91	10.1	1.07	51.9	20,440	7.7
Rural	**5%**	6.8	≤0.10	≤2.0	0.12	≤2.0	≤50	1.0
	10%	15.4	≤0.10	≤2.0	0.13	≤2.0	77	1.0
	25%	34.4	≤0.10	≤2.0	0.18	4.7	368	1.8
	50%	47.5	0.18	3.1	0.30	12.6	934	4.1
	75%	55.3	0.46	7.4	0.64	27.8	2,061	7.6
	90%	61.5	0.86	14.0	1.24	49.4	3,946	10.2
	95%	64.5	1.11	17.6	1.55	63.4	5,955	11.5
urban	**5%**	1.7	≤0.10	≤2.0	0.13	1.0	≤50	1.0
	10%	4.6	≤0.10	≤2.0	0.15	1.7	≤50	1.0
	25%	13.7	0.15	≤2.0	0.23	6.1	82	1.3
	50%	28.4	0.34	3.2	0.42	19.5	244	2.6
	75%	43.1	0.67	6.4	0.75	40.5	661	4.8
	90%	53.5	1.07	11.0	1.20	59.9	1,213	7.6
	95%	59.5	1.34	14.0	1.48	72.5	1,694	9.2

Table 2c: Overview of the distributions of parameters related to non-exhaust emissions in Japan

Significant differences between Europe and Asia were observed when "extreme" conditions in rural areas and motorways were investigated. Average speeds and standing duration of the vehicles exhibited the biggest difference. In general, it is noted that rural and urban areas in Asia are quite similar. On the other hand, similar threshold values for accelerations, decelerations and braking phase durations are found among Europe and

Asia with European values being slightly higher. Table 2e summarizes median and Table 2f threshold values of all parameters for the examined regions and road categories.

Korea	Cum Frequency	Vehicle Speed [km/h]	Acceleration [m/s^2]	Deceleration Duration [s]	Deceleration [m/s^2]	Stop Duration [s]	Short Trip Distance [m]	Brake Phase Duration [s]
Motorway	5%	2.6	≤0.10	≤2.0	0.11	1.0	≤50	1.0
	10%	6.0	≤0.10	≤2.0	0.13	1.4	≤50	1.0
	25%	15.5	≤0.10	2.4	0.17	3.2	86	1.5
	50%	46.0	0.17	4.0	0.27	6.2	344	2.7
	75%	73.9	0.33	6.9	0.45	12.3	4,392	4.4
	90%	85.7	0.55	11.1	0.74	24.1	24,400	7.2
	95%	91.1	0.72	14.7	1.00	46.1	49,400	9.2
Rural	5%	10.0	≤0.10	≤2.0	0.12	≤2.0	46	1.0
	10%	18.8	≤0.10	≤2.0	0.14	2.2	126	1.2
	25%	33.7	0.10	2.7	0.20	6.2	541	2.3
	50%	48.6	0.24	4.7	0.35	16.9	1,575	3.7
	75%	60.6	0.48	8.0	0.69	43.5	3,435	5.9
	90%	73.1	0.79	13.4	1.24	69.7	7,943	9.3
	95%	79.3	0.99	17.6	1.60	90.2	15,485	11.5
urban	5%	1.2	≤0.10	≤2.0	0.12	1.3	≤25	1.0
	10%	3.6	≤0.10	≤2.0	0.15	2.8	25	1.1
	25%	12.6	0.13	2.9	0.22	6.6	112	2.0
	50%	27.2	0.31	5.2	0.41	21.9	322	3.7
	75%	40.5	0.59	9.5	0.77	51.4	698	6.5
	90%	50.2	0.92	14.2	1.19	87.1	1,166	9.2
	95%	56.4	1.13	17.3	1.47	102.2	1,654	10.6

Table 2d: Overview of the distributions of parameters related to non-exhaust emissions in Korea

Region	Road Type	Vehicle Speed [km/h]	Acceleration [m/s^2]	Deceleration Duration [s]	Deceleration [m/s^2]	Stop Duration [s]	Short Trip Distance [m]	Brake Phase Duration [s]
Europe	Mtr	114.8	0.27	3.5	0.38	6.2	4,290	2.5
	Rur	64.7	0.35	4.3	0.47	5.9	1,736	3.4
	Urb	28.3	0.45	4.7	0.55	5.8	264	3.3
India	Mtr	55.0	0.15	3.8	0.27	6.2	1,839	2.7
	Rur	37.0	0.19	4.0	0.30	5.9	2,558	2.8
	Urb	25.0	0.21	3.9	0.32	6.2	576	2.6
Japan	Mtr	62.8	0.18	2.0	0.28	6.1	143	1.6
	Rur	47.5	0.18	3.1	0.30	12.6	934	4.1
	Urb	28.4	0.34	3.2	0.42	19.5	244	2.6
Korea	Mtr	46.0	0.17	4.0	0.27	6.2	344	2.7
	Rur	48.6	0.24	4.7	0.35	16.9	1,575	3.7
	Urb	27.2	0.31	5.2	0.41	21.9	322	3.7

Table 2e: Overview of median (50th percentile) distributions of non-exhaust related parameters worldwide

Region	Road Type	Vehicle Speed [km/h]	Acceleration [m/s^2]	Deceleration Duration [s]	Deceleration [m/s^2]	Stop Duration [s]	Short Trip Distance [m]	Brake Phase Duration [s]
Europe	Mtr	137.9	0.98	14.6	1.20	48.4	79,094	10.3
	Rur	113.7	1.31	16.9	1.70	52.0	26,086	10.2
	Urb	60.2	1.35	14.5	1.70	55.0	3,270	9.0
India	Mtr	83.9	0.74	13.7	1.19	93.1	52,700	8.7
	Rur	68.7	0.82	12.8	1.36	102.8	35,575	7.6
	Urb	65.2	0.80	13.2	1.21	74.0	7,912	7.9
Japan	Mtr	99.7	0.91	10.1	1.07	51.9	20,440	7.7

	Rur	64.5	1.11	17.6	1.55	63.4	3,946	11.5
	Urb	59.5	1.34	14.0	1.48	72.5	1,694	9.2
Korea	**Mtr**	91.1	0.72	14.7	1.00	46.1	49,400	9.2
	Rur	79.3	0.99	17.6	1.60	90.2	15,485	11.5
	Urb	56.4	1.13	17.3	1.47	102.2	1,654	10.6

Table 2f: Overview of extreme (95th percentile) distributions of non-exhaust related parameters worldwide

5 Vehicle speeds

Figure 1 shows the time weighted vehicle speed distribution curves for the different countries as well as for the different campaigns within the same country. Significant differences are observed when European and Asian data are compared. US data seem to be close to European. For instance, median average vehicle speeds of 40 km/h are observed in Asian territories, while in some European countries (Belgium, Slovenia, Italy) median speed was higher than 50 km/h. US median average vehicle speed was found to be somewhat higher than 50 km/h. In some cases significant differences are observed even within European data. For instance, the measurement campaigns in Poland and Spain are dominated by urban traffic conditions (90% of average speeds are lower than 65 and 85 km/h, respectively), while the campaign in Italy has a high influence of rural and motorway traffic (45% and 35% of average speeds are higher than 65 and 85 km/h, respectively). Furthermore, some smaller differences between the individual vehicles (drivers) within a country are also observed particularly when data from the Asian region are examined.

From Figure 1 it is difficult to define a worldwide threshold value of the speed beyond which the driving behaviour could be characterized as “extreme”. For instance, in India speeds higher than 65-85 km/h fall in the range above the 95th percentile, while for some European countries (Belgium, Italy, France, Germany) as well as for the US the threshold speed is close to 120 km/h. For that reason it is proposed to conduct this type of investigation with data separated for the different road categories (see chapter 4 – Table 2f). On the contrary, average speeds lower than 2 km/h could be globally considered as threshold values and therefore inappropriate for studying representative real world conditions (lower 5th percentile).

It has to be noted that data from India, Japan and Korea are not customer data, but results from well-designed measurement campaigns dedicated to be representative for these countries.

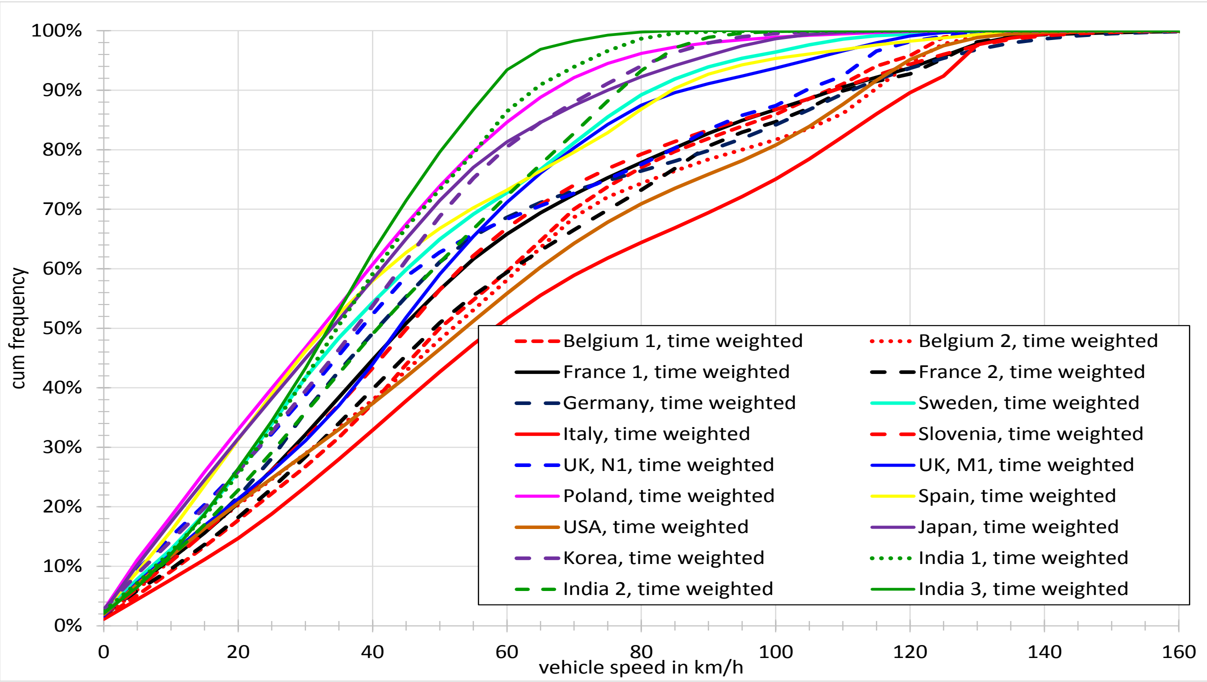


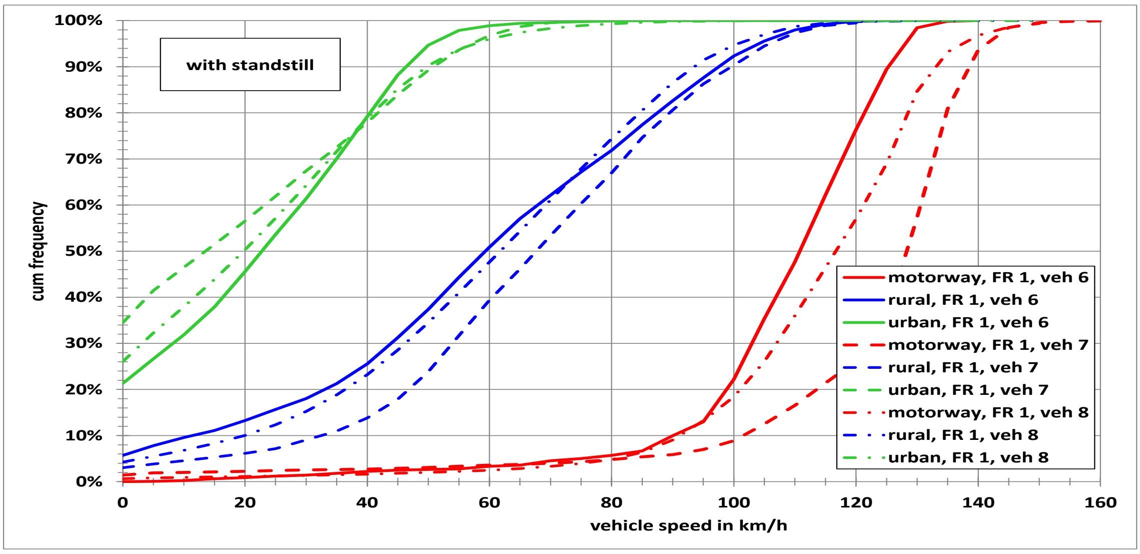
Figure 1: Time weighted speed distributions (without stop times) for the different countries

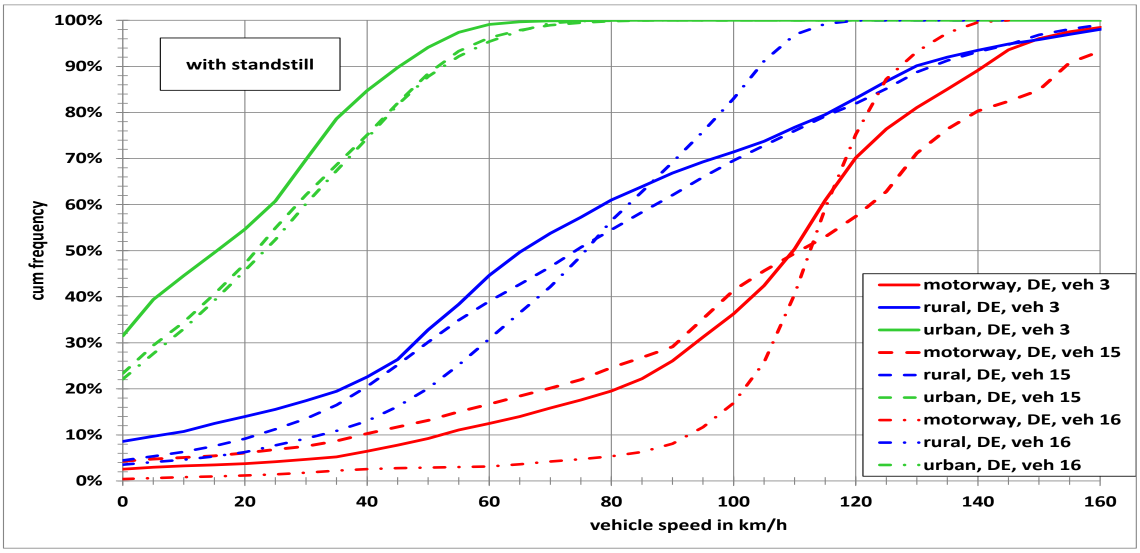
The customer datasets Belgium 1, France 1, France 2, Germany, Italy, Slovenia, UK M1, Poland and Spain came along with road category indicators for urban, rural and motorway. This way it was able to calculate the key parameters of these datasets and more specifically the parameters related to mileage, driving time and average speeds per country (Table 3).

	Distance share [%]			Time share [%]			Average Speed with stops [km/h]			Average Speed without stops [km/h]		
Country	**Mot/way**	**Rural**	**Urban**	**Mot/way**	**Rural**	**Urban**	**Mot/way**	**Rural**	**Urban**	**Mot/way**	**Rural**	**Urban**
Belgium	38.1	50.4	11.5	21.3	57.1	21.5	89.6	44.3	26.9	92.7	50.4	32.8
France 1	27.6	44.0	28.3	11.0	34.2	54.8	116.1	59.5	24.0	117.0	62.7	31.1
France 2	22.9	53.7	23.4	9.6	41.2	49.2	117.8	64.2	23.4	118.6	67.2	31.4
Germany	19.4	46.6	34.0	8.4	28.8	62.7	107.6	75.8	25.4	109.2	78.4	31.0
Italy	40.5	41.6	17.9	22.5	37.0	40.5	109.4	68.2	26.8	109.9	70.6	32.8
Slovenia	20.3	49.3	30.4	8.8	33.6	57.6	106.9	68.3	24.5	108.5	70.9	31.2
UK	3.1	55.2	41.7	1.3	35.9	62.7	100.5	67.1	29.1	101.5	68.7	34.1
Poland	2.5	32.8	64.7	0.7	17.1	82.3	104.3	55.9	22.9	105.2	61.0	30.2
Spain	10.6	50.7	38.7	3.0	25.2	71.8	112.0	63.9	17.1	114.0	66.5	26.5

Table 3: Key parameters with respect to mileage, driving time and speeds in Europe

Indicative road category specific vehicle speed distributions for individual vehicles from France, Germany and Italy are provided in Figure 2a-c.





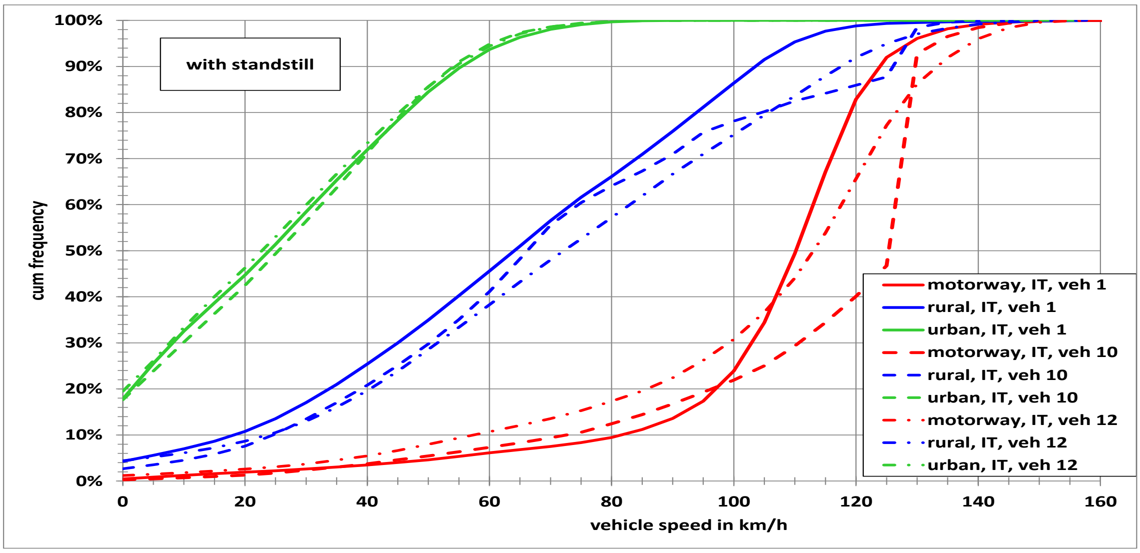


Figure 2: Vehicle speed distributions for different road categories in the European campaign: a (France), b (Germany), and c (Italy)

Median speeds (50th percentile) in the urban areas of the three countries ranged from 15-25 km/h, which is somewhat lower than the median European value of 28.3 km/h (Table 2e). Higher deviations were observed in rural areas (60-85 km/h) and motorways (110-130 km/h), with however the values being within the median European speeds (64.7 and 114.8 km/h, respectively). Also, some differences between the individual vehicles (drivers) within a country were observed particularly for motorway data. Another conclusion from the study is that data for Belgium are quite inhomogeneous and show high percentages of saturated and/or congested traffic, especially on motorways.

6 Short trip and stop phase analysis

6.1 Stop phases

In order to assess the structure of the in-use driving behaviour data with respect to the number of stops, the distances driven between the stops etc., the data was separated into stop periods and short trips. Stop periods are defined as connected time sequences with vehicle speeds below 1 km/h. Short trips are connected time sequences with vehicle speeds ≥ 1 km/h.

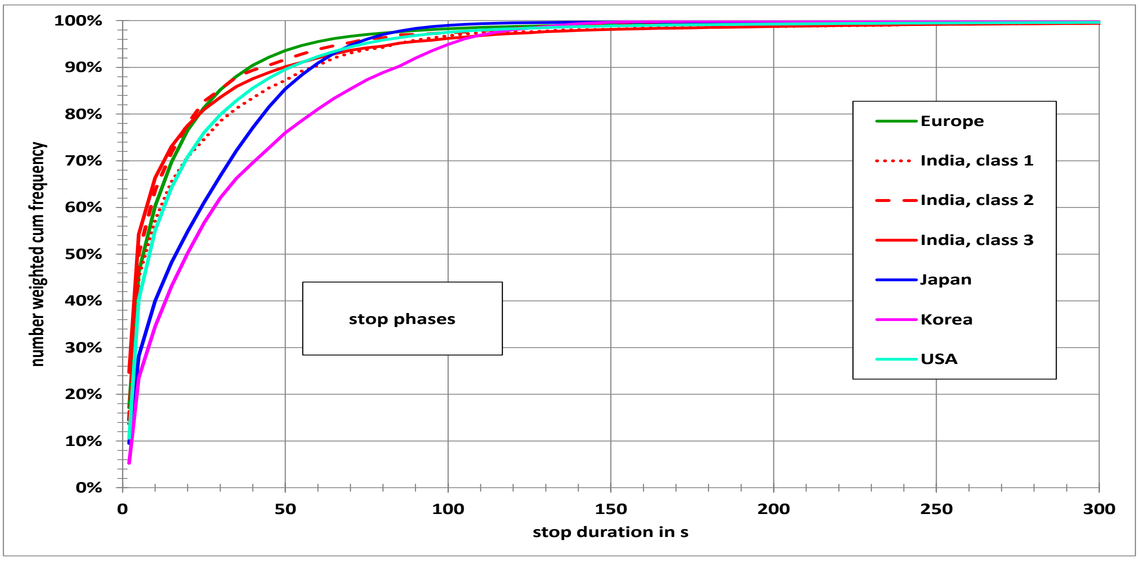


Figure 3: Stop duration distributions (number weighted) for different regions

Figure 3 shows the number weighted stop phase duration distributions for different regions worldwide. Number weighted means that the percentages on the y-axis indicate the percentage of the whole number of stop phases with a duration that corresponds to the x-axis value. It can be seen that median stop phases in Korea and Japan are generally longer (~20 s) compared to the rest of the database (~6 s). It is clear that stop phases in Europe and the USA are not only linked with traffic lights but also with spots with intensive traffic and therefore continuous use of the brakes. When it comes to the threshold value in order to define "extreme" stop duration (i.e. 95th percentile) the differences among regions are more distinct. While for Europe and the US stop durations longer than 60 s could be characterized as **"extreme"**, in Korea and India only stops longer than 90 s fall in the range of 95th - 100th percentile. These observations are in line with those described in chapter 4 and more particular with the information provided in Tables 2a to 2f.

Figure 4 shows the number weighted stop duration distributions for Europe separated into the three road categories (i.e. urban, rural and motorway). As described previously, vehicles in European roads stay steel for no longer than 55 s, regardless the road category (95th percentile). On the other hand, median stop duration in urban and rural areas is approximately 6.0 s, while in motorways is slightly higher (6.2 s).

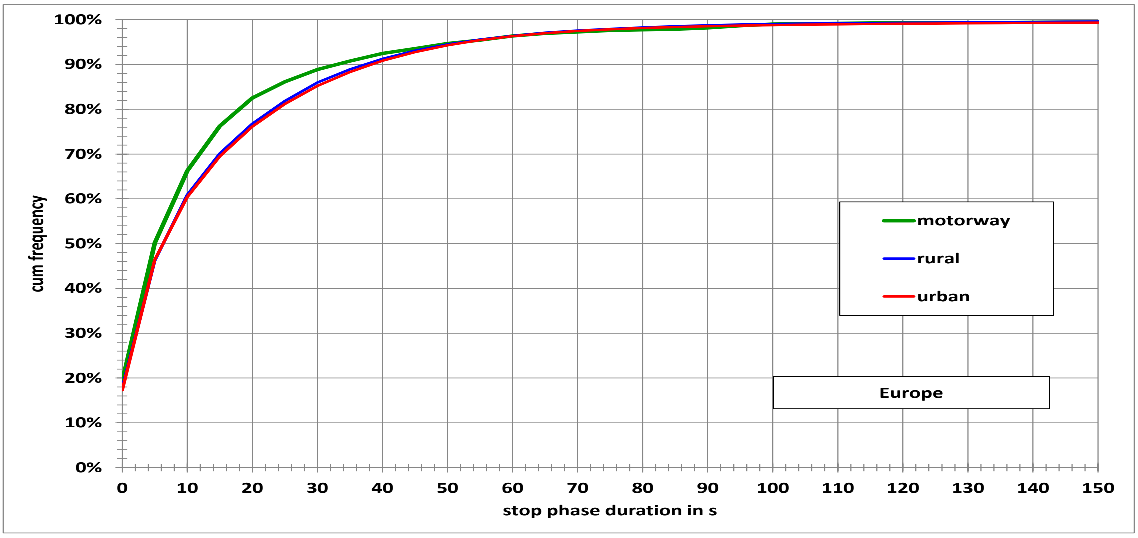


Figure 4: Stop duration distributions (number weighted) for different road categories

6.2 Short trips

Figure 5 shows the short trip distance distributions for different regions number weighted. Median short trip distance (50^{th} percentile) is less than 1 km worldwide, while most trips (95^{th} percentile) are not longer than 10 km at least in Europe and the US. The picture regarding the "extreme" short trip distance is different only in India probably due to differences in the fleet and roads.

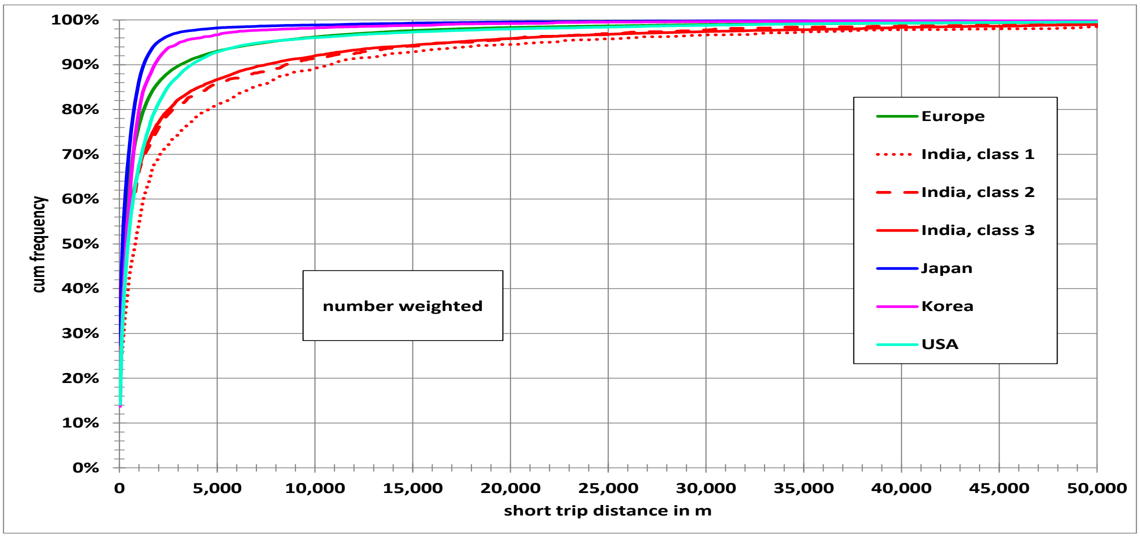


Figure 5: Short trip distance distributions (number weighted) for different regions

Figure 6 shows number weighted short trip distance distributions for Europe, separated for different road categories. Average short trip distance differs significantly among the road categories, while "threshold" values are almost one order of magnitude different. In general, short trips in motorways are much longer than those of urban and rural areas.

In order to assess the occurrence of creeping situations the short trips were binned with respect to their maximum speed and the distances were summed up per max speed bin and related to the total distance. The results are shown for different regions in Table 4. Based on the assumption that the majority of trips with max speed of 5 km/h as well as a big part of trips with max speed of 15 km/h can be attributed to creeping situations it comes out that in Korea and the US almost 10% of the short trips are linked to intensive traffic jams, while in Europe and Japan more than 1 out of 5 trips occur within a creeping situation. Finally, from Table 4 it can be deduced that the median max speed of short trips in Japan (number weighted) is approximately 25 km/h, in Europe approximately 35 km/h, and in the US somewhat higher (~ 45 km/h).

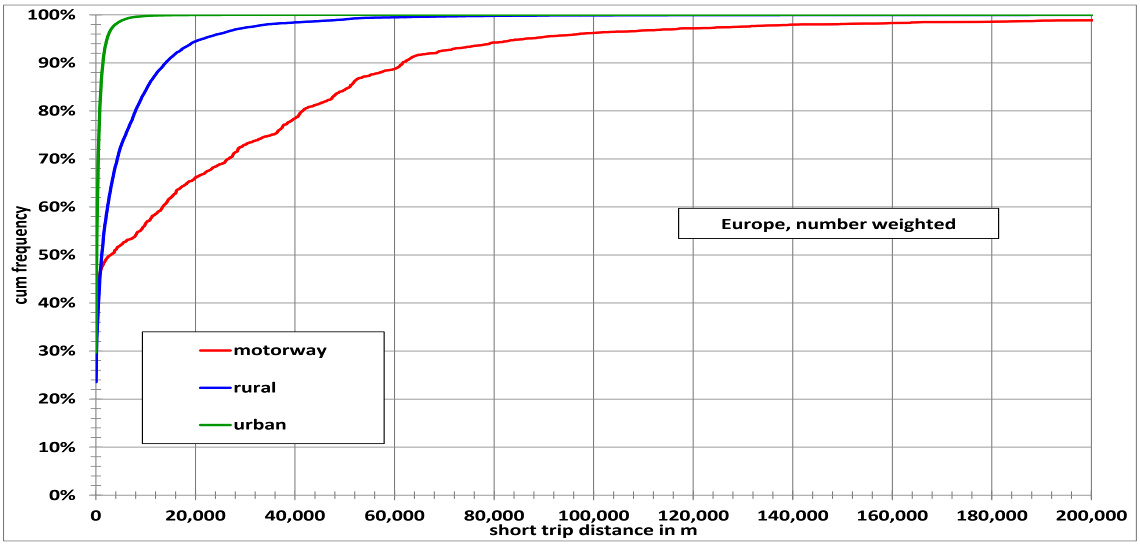


Figure 6: Short trip distance distributions for Europe separated for road categories

Number [#] and Share [%] of Short trips										
V max [km/h]	Europe		India		Japan		Korea		USA	
5	47575	**20.2**	5077	**29.6**	12857	**19.1**	2741	**9.8**	5376	**9.6**
15	28789	**12.2**	1778	**10.4**	8964	**13.3**	2633	**9.4**	4882	**8.7**
25	23526	**10.0**	1367	**8.0**	9143	**13.6**	3394	**12.1**	4598	**8.2**
35	26881	**11.4**	1913	**11.2**	9355	**13.9**	3841	**13.7**	5148	**9.1**
45	31773	**13.5**	2165	**12.6**	9663	**14.4**	5290	**18.9**	5802	**10.3**
55	27123	**11.5**	1722	**10.1**	9018	**13.4**	4917	**17.6**	6752	**12.0**
65	17145	**7.3**	1194	**7.0**	5124	**7.6**	2480	**8.9**	7390	**13.1**
75	10757	**4.6**	858	**5.0**	1668	**2.5**	1291	**4.6**	6079	**10.8**
85	6812	**2.9**	677	**4.0**	555	**0.8**	801	**2.9**	4051	**7.2**
95	4826	**2.1**	289	**1.7**	341	**0.5**	326	**1.2**	2065	**3.7**
105	3018	**1.3**	78	**0.5**	293	**0.4**	183	**0.7**	1122	**2.0**
115	2309	**1.0**	9	**0.1**	148	**0.2**	69	**0.2**	994	**1.8**
125	1907	**0.8**	4	**0.0**	47	**0.1**	16	**0.1**	1072	**1.9**
>135	2655	**1.2**	1	**0.0**	19	**0.0**	10	**0.0**	935	**1.6**

Table 4: Number and share of short trips in different max speed bins for different regions

7 Acceleration phases

Acceleration phases are specified as consecutive time samples with a > 0.5 km/h/s or 0.1389 m/s². In order to ease the calculation of duration and distance related distributions the results were binned for both values (2.0 s duration and 5.0 m distance).

7.1 Duration distributions

Vehicle specific acceleration phase duration distributions for different regions worldwide for short trips with maximum speed ≤ 60 km/h are shown in Figure 7a. It can be seen that the distributions are similar in all regions. For instance, the median acceleration phase duration as expressed by the 50th percentile of the distribution varies from 3.0-5.0 s with most values being close to 4.0 s. Similarly the 95th percentile value of the duration distribution varies from 15 to 17 s with the exception of Korea where the acceleration phase duration is higher (20 s).

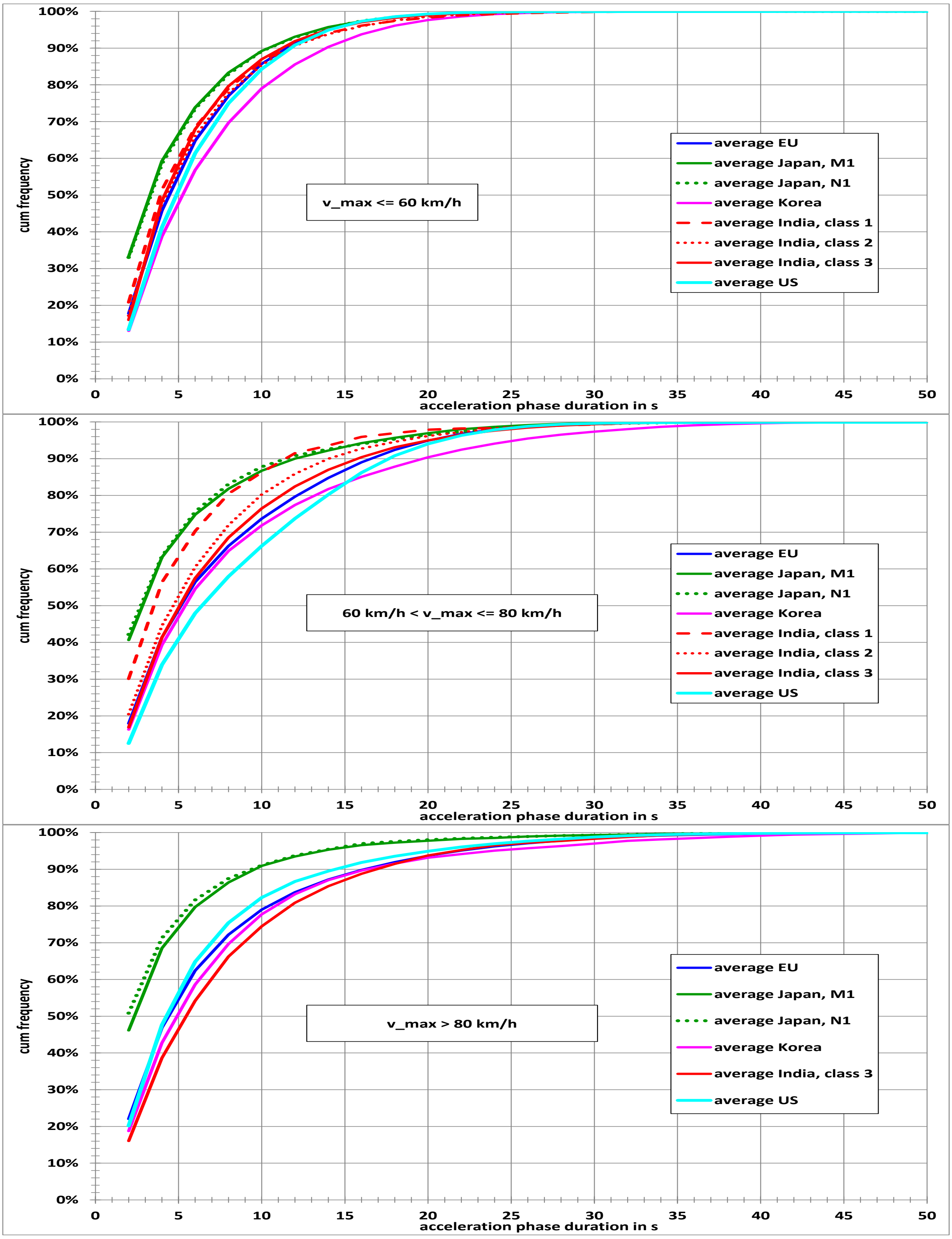


Figure 7: Acceleration phase duration distributions [s] for different maximum speed category worldwide: a. (≤ 60 km/h), b. (60 km/h < max speed ≤ 80 km/h), and c. (> 80 km/h)

Figure 7b and 7c show the corresponding distributions for acceleration phases with maximum speed between 60 and 80 km/h and above 80 km/h, respectively. The picture here is a bit different as Japanese data are clearly "softer" compared to the median values in Europe and the US (acceleration phase duration of ~2.0 s vs. ~6.0 s), while the US data show longer acceleration phases over the urban and rural parts of the database (i.e. speed categories with max speed under 80 km/h).

Figure 8 shows a comparison of the average curves for Europe with the different maximum speed ranges. It can be seen that median acceleration phase duration for all speed categories is approximately 5.0 s. On the other hand, 95% of acceleration phases in urban areas last less than 14 s while for rural and motorway areas more than 20 s. These durations could be considered as threshold for extreme driving behaviour.

Class 1, 2 and 3 vehicles are vehicles with a rated power to kerb mass ratio ≤ 22 W/kg, between 22 W/kg and 34 W/kg, and > 34 W/kg, respectively.

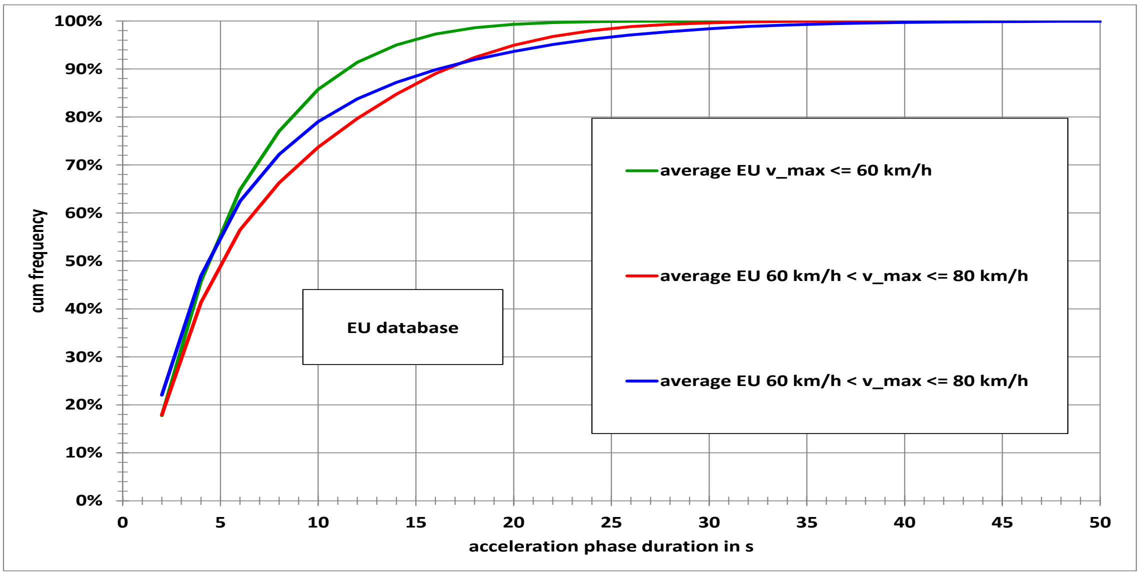


Figure 8: Acceleration phase duration distributions for short trips with different max speed

7.2 Distance distributions

Vehicle specific distance distributions for the different regions and for acceleration phases with max speed ≤ 60 km/h are shown in Figure 9a. Median acceleration distance (50^{th} percentile) in all places is approximately 40 m with Japanese data showing once more "softer" acceleration phases (approximately 25 m). On the other hand, acceleration distances longer than 150 m can be considered as **"extreme"**. Once more it seems that European and US data can be treated as similar.

Figure 9b and 9c show the corresponding distributions for acceleration phases with maximum speed between 60 and 80 km/h and above 80 km/h, respectively. Once more Japanese data seem to differ significantly both for average and threshold acceleration phase distances. The US data show this time longer acceleration phases in terms of distance covered over the rural and motorway part of the database (i.e. speed categories with max speed over 60 km/h).

Figure 10 shows a comparison of the average curves for Europe with the different max speed ranges. It can be seen that 95% of acceleration phases in urban areas occur within 120 m, in rural areas within 280 m and in motorway areas within 500 m. These distances could be considered as threshold for **"extreme"** driving behaviour.

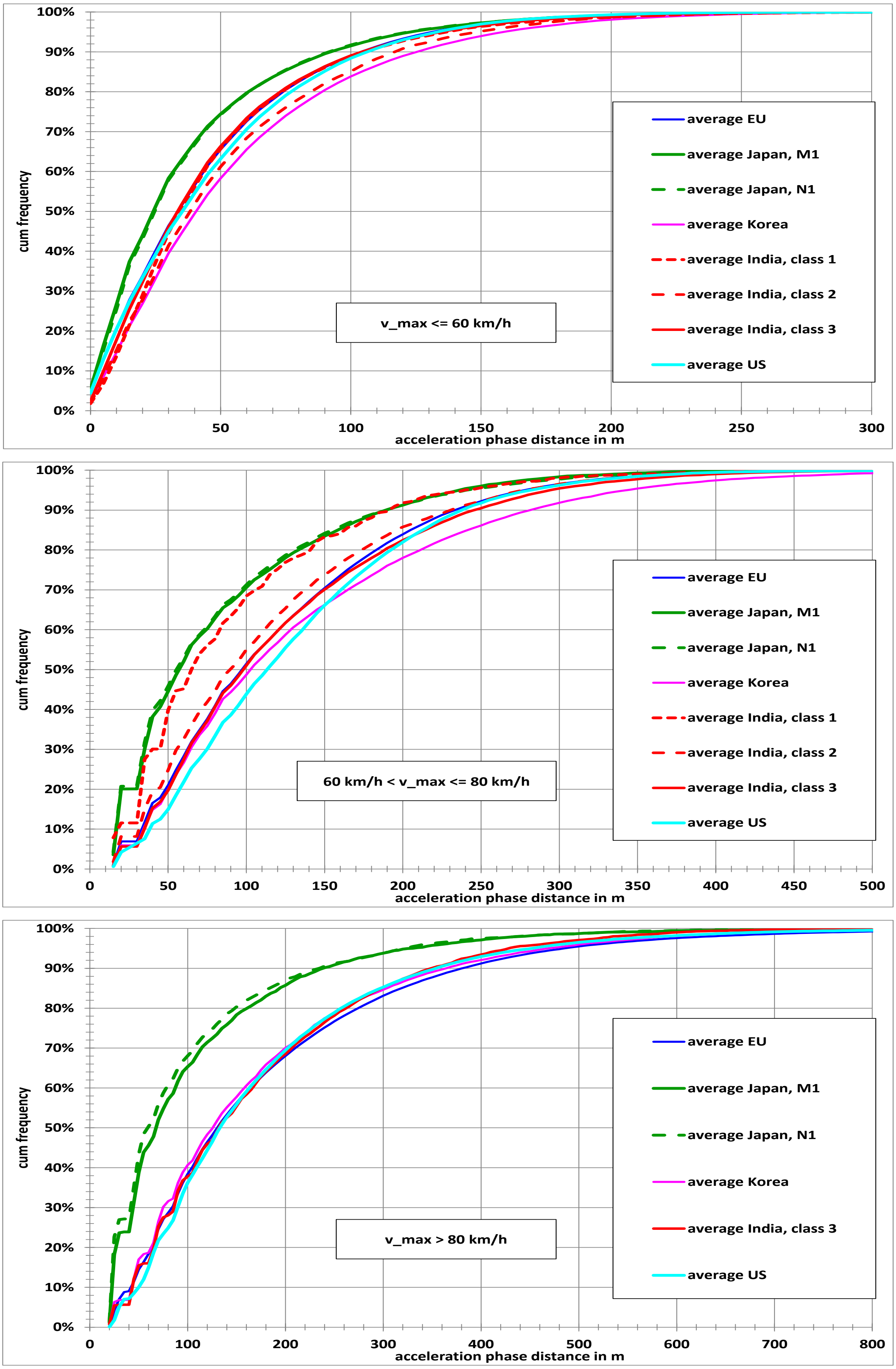


Figure 9: Acceleration phase distance distributions [m] for different maximum speed category worldwide: a (≤ 60 km/h), b (60 km/h < max speed ≤ 80 km/h), and c (> 80 km/h)

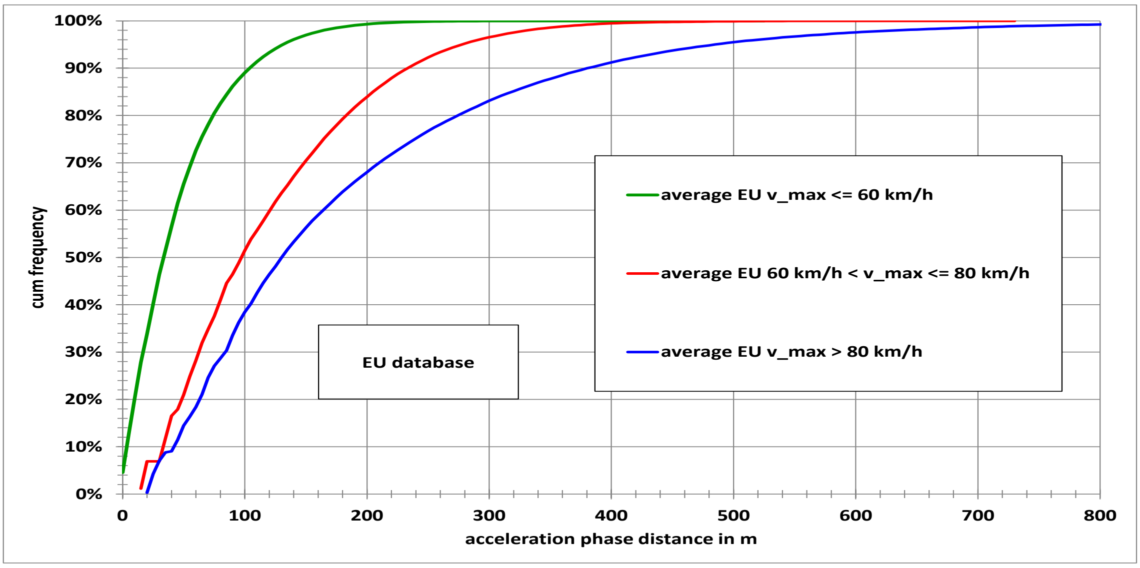


Figure 10: Acceleration phase distance distributions for short trips in Europe with different max speeds

8 Deceleration phases

Deceleration phases are specified as consecutive time samples with a < -0.5 km/h/s or -0.1389 m/s². In order to ease the calculation of duration and distance related distributions the results were binned for both values (2.0 seconds for the duration and 5 m for the distance). The analysis was performed for phases up to 60 km/h, between 60 and 80 km/h and above 80 km/h separately.

8.1 Duration distributions

Vehicle specific duration distributions for the different regions and for deceleration phases with maximum speed lower than 60 km/h are shown in Figure 11a. Deceleration phase distributions seem to be similar for all regions at least when this particular speed category is examined. Median (50^{th} percentile) deceleration phase duration varies from 3.0 to 5.0 s with most values being around 4.0 s. Similarly the 95^{th} percentile duration varies from 13 to 17 s with the most values being close to 15 s. This would practically mean that decelerations longer than 15 s could be characterized as "extreme".

Figures 11b and 11c demonstrate the corresponding distributions for deceleration phases with maximum speed between 60 and 80 km/h and above 80 km/h. In these cases there are some differences among the regions examined with data from Japan and India pointing to shorter deceleration phases as a result to generally lower average speeds (see chapter 7). The US data show once more longer deceleration phases over the urban and rural parts of the database (i.e. speed categories with max speed under 80 km/h). In any case decelerations longer than 20 s could be considered as **"extreme"** regardless the speed category examined.

Figure 12 shows a comparison of the average curves for Europe with the different maximum speed ranges. It can be seen that 95% of deceleration phases of short trips with maximum speed lower than 60 km/h (mostly urban related short trips) last less than 13 s, while for higher speeds the deceleration duration exceeds 20 s. Once more these durations could be considered as threshold for **"extreme"** driving behaviour in the European region. This assumption is confirmed from Table 2f where threshold deceleration durations for all road categories are provided.

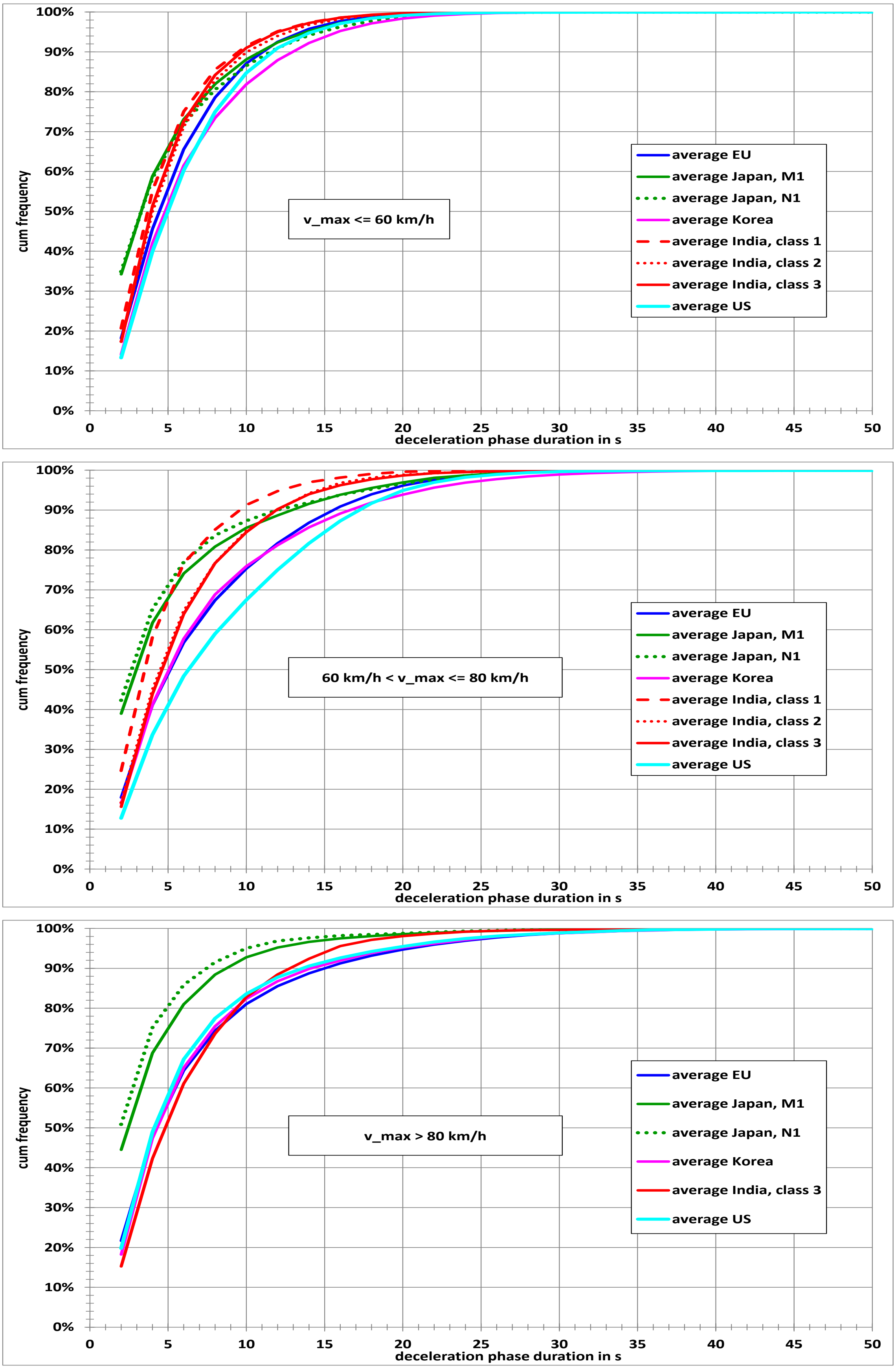


Figure 11: Deceleration phase duration distributions for the different regions and different max speeds: a (≤ 60 km/h), b (60 km/h < max speed ≤ 80 km/h), and c (> 80 km/h)

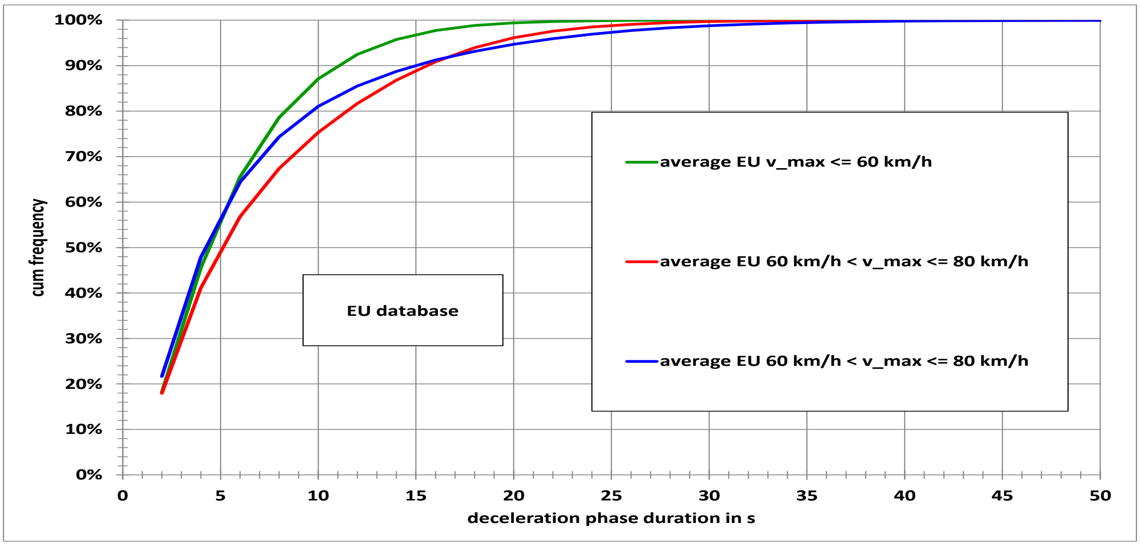


Figure 12: Deceleration phase duration distributions for short trips with different max speed

8.2 Distance distributions

Vehicle specific distance distributions for the different regions and for deceleration phases with max speed ≤ 60 km/h are shown in Figure 13a. Median deceleration distance in all places worldwide except for Japan was found to be approximately 40 m. Deceleration distances longer than 150 m can be considered as a result of **"extreme"** driving behaviour. Once more, Japanese data can be considered "softer" in terms of accelerations and decelerations compared to the rest of the world. Figures 13b and 13c show the corresponding distributions for deceleration phases with max speed between 60 and 80 km/h and above 80 km/h. Japanese data seem to differ significantly both for median and threshold deceleration phase distances, while the US data show longer deceleration phases for higher speeds.

Figure 14 shows a comparison of the average curves for Europe with the different max speed ranges. It can be seen that 95% of deceleration phases in urban areas occur within 120 m, in rural areas within 250 m and in motorway areas within 450 m. These distances could be considered as threshold for **"extreme"** driving behaviour.

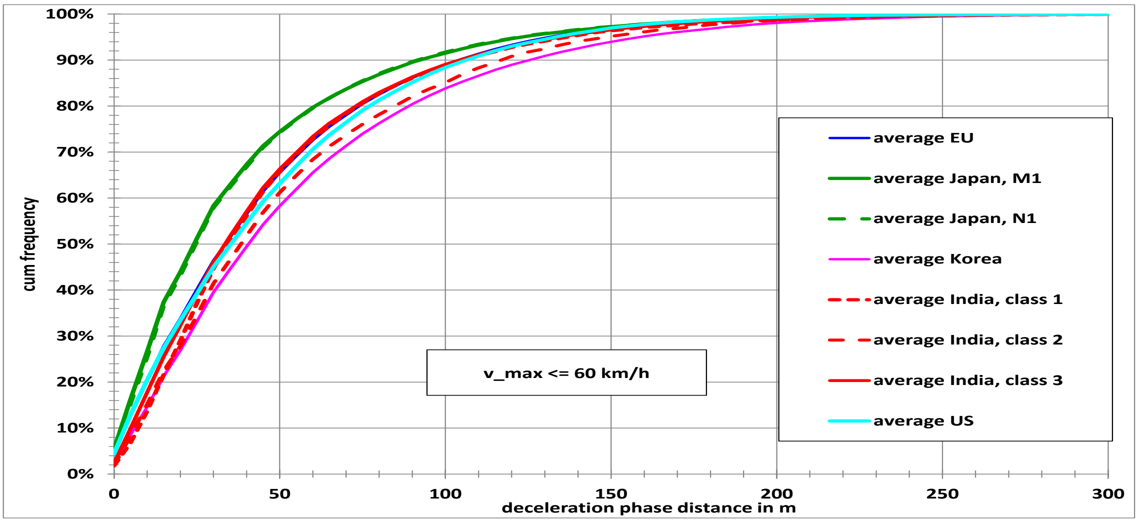
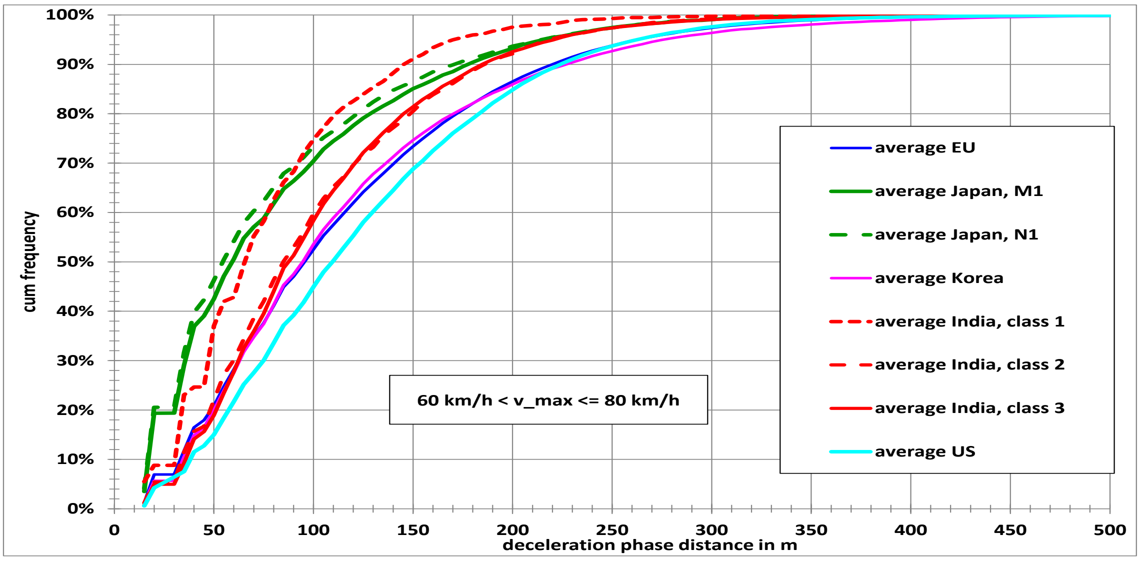


Figure 13a: Deceleration phase duration distributions for the different regions and max speed ≤ 60 km/h



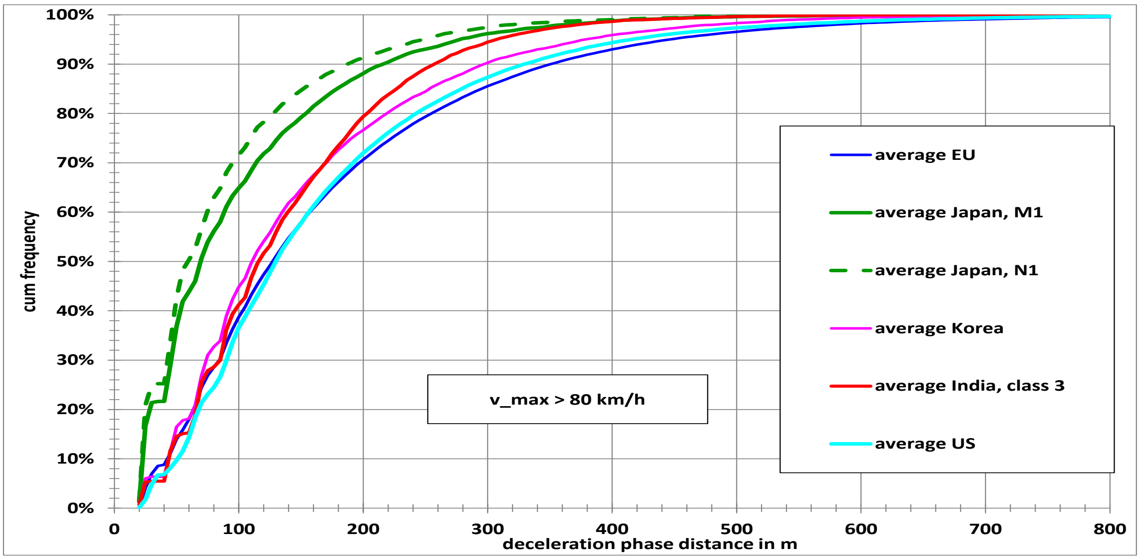


Figure 13: Deceleration phase duration distributions for the different regions and maximum speed categories: b (60 km/h < max speed ≤ 80 km/h) and c (> 80 km/h)

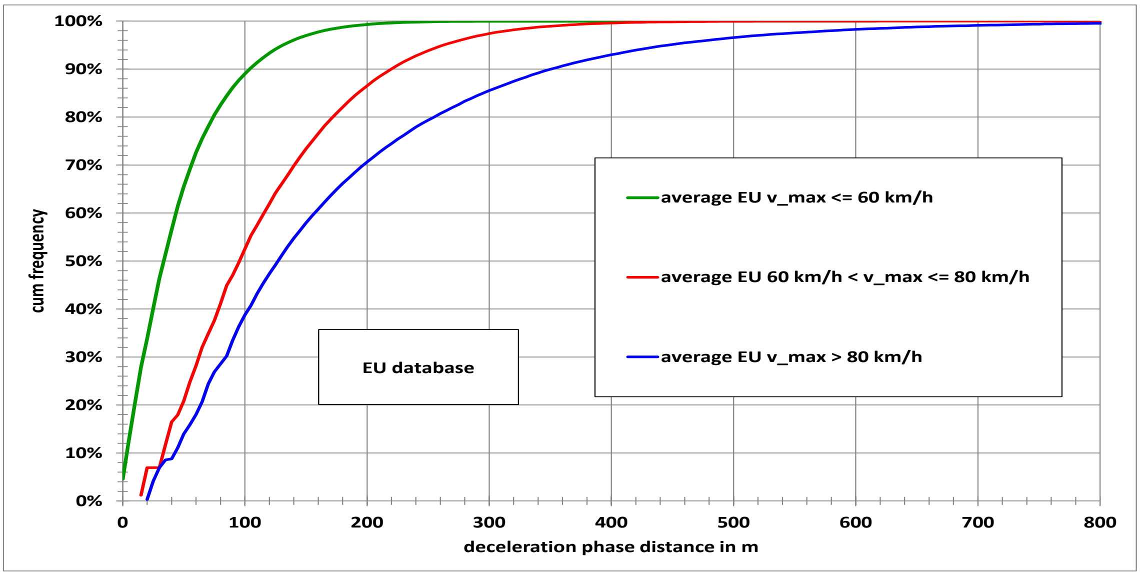


Figure 14: Deceleration phase distance distributions for short trips with different max speeds

9 Phases with brake engaged

9.1 Determination of a speed dependent decel threshold curve

Another objective of the current analysis is the determination of the distributions i. of the duration of braking events and ii. of the distance covered by the vehicle during the brake use. The brake use during deceleration phases should be determined by expert guess thresholds for the deceleration. Fortunately, an alternative method was able to be used, due to the availability of in-use driving behaviour data from research project of the German Environment Agency, dedicated to the improvement of the type approval noise measurement method for light duty vehicles ("Investigations on Improving the Method of Noise Measurement for Powered Vehicles", July 1997). Within this project in-use driving behaviour measurements were performed with 11 cars in Aachen and the surroundings, where vehicle speed, engine speed and drive axle torque, but also clutch and brake engagement was measured.

Several threshold curves were tested and the resulting brake use duration and distance distributions were compared with the measured ones. The best fit was achieved for the following vehicle speed dependent deceleration threshold curve:

$$a\_threshold = -0.098468 * \ln(v) - 0.30439$$

This leads in the following polynomial function for a corresponding v*a threshold curve:

$$v*a\_threshold = 7.83392E\text{-}07*v^3 - 4.10447E\text{-}04*v^2 - 1.80147E\text{-}01*v + 3.35105E\text{-}01$$

Both curves are shown in Figure 15. When vehicles with automatic transmissions are disregarded, the calculated distributions are in sufficiently good *agreement with* the measured distributions and therefore the proposed approach is more than satisfactory.

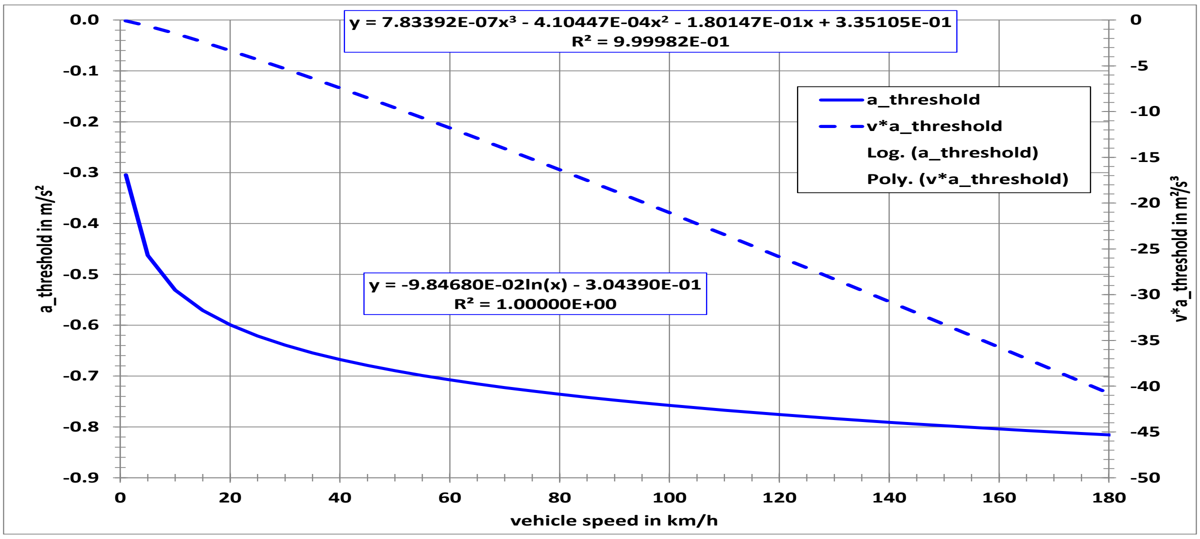


Figure 15: Threshold curves for the determination of brake engagement phases

9.2 Results for the WLTP database

9.2.1 Brake phase duration distributions

Vehicle specific duration distributions for the different regions and for deceleration phases with different max speed categories are shown in Figure 16.

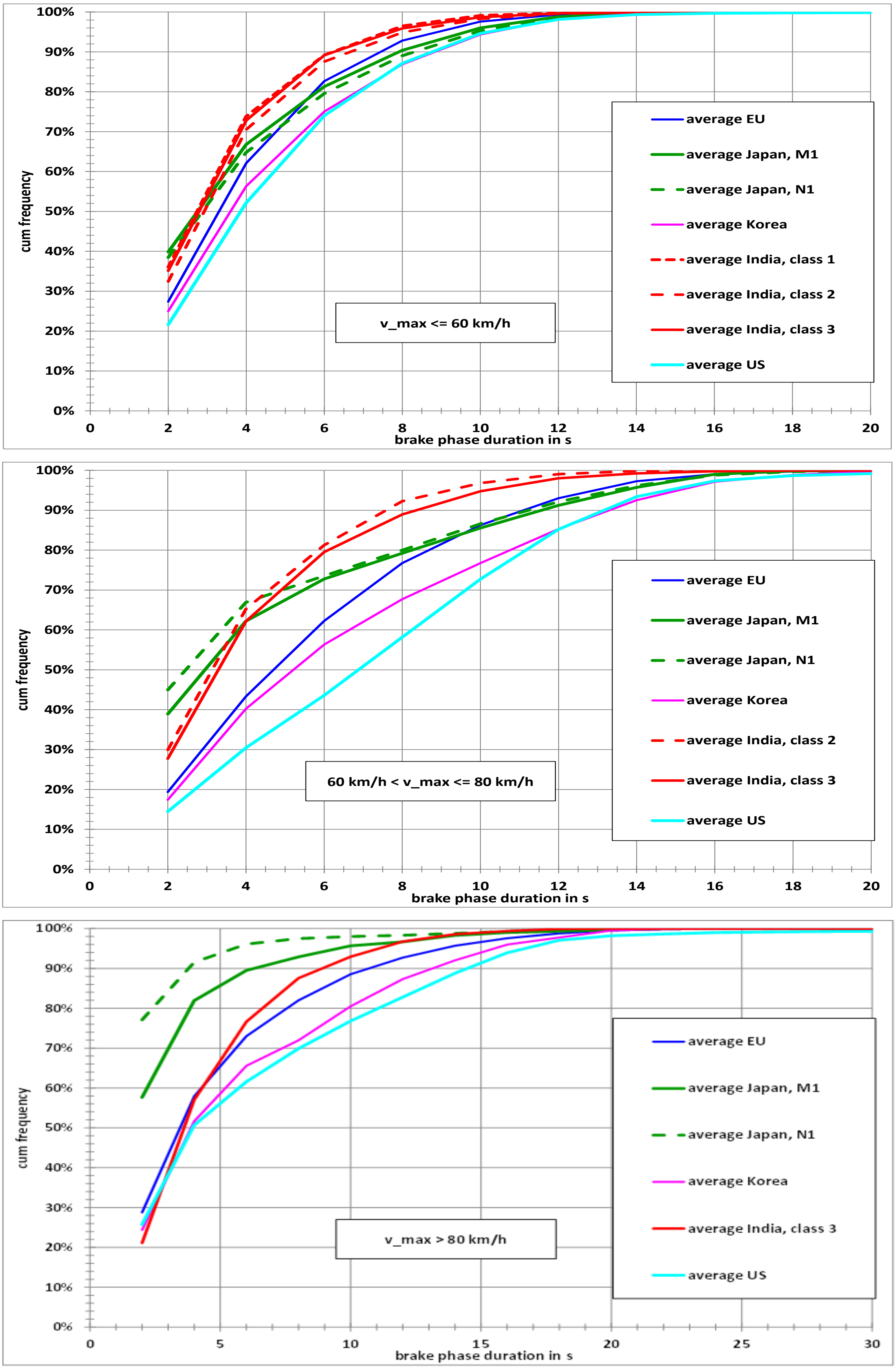


Figure 26: Brake phase duration distributions for the different regions and maximum speed categories: a. (max speed ≤ 60 km/h), b. (60 km/h < max speed ≤ 80 km/h), c. (max speed > 80 km/h)

It can be seen from Figure 16a that for Japan and India the median brake phase duration is approximately 3.0 s, while EU, US and Korean data showed slightly higher median brake phase duration (3.5-4.0 s). These figures are in line with those presented in Chapter 3 (Table 2e) for the urban areas of all regions showing that the majority of short trips with max speed of 60 km/h occur in urban areas. Threshold value for the brake duration for short trips with max speed of 60 km/h (95th percentile) seems to be close to 10 s for all regions except for India (~8 s).

Regarding the distributions for deceleration phases with max speed between 60 and 80 km/h and above 80 km/h, the picture is not similar with drivers behaving differently depending on the region. For instance, while for medium max speeds Japanese and Indian drivers push their brakes in average for 3.0 s (50th percentile), drivers from Europe and the US brake in average for about 5.0 s and 7.0 s, respectively (Figure 16b). Finally, it is noteworthy that in Asia for short trips with max speeds >60 km/h more than 30% of the braking events are shorter than 2.0 s.

Figure 17 shows a comparison of the average curves for Europe with the different maximum speed ranges. It can be seen that for short trips with maximum speed lower than 60 km/h (i.e. mostly data from urban areas) and higher than 80 km/h (i.e. mostly data from motorways) the median brake phase duration is 3 s, while for medium speeds the median brake duration is almost 4.5 s. These values are in-line with those given for different road categories in Table 2a. Threshold values for the brake duration (95th percentile) seem to be close to 9 s for speeds lower than 60 km/h and 12 s for higher speeds. In general, brake phase duration longer than 12 s can be considered as "extreme". In all cases more than 20% of the braking events are shorter than 2 s.

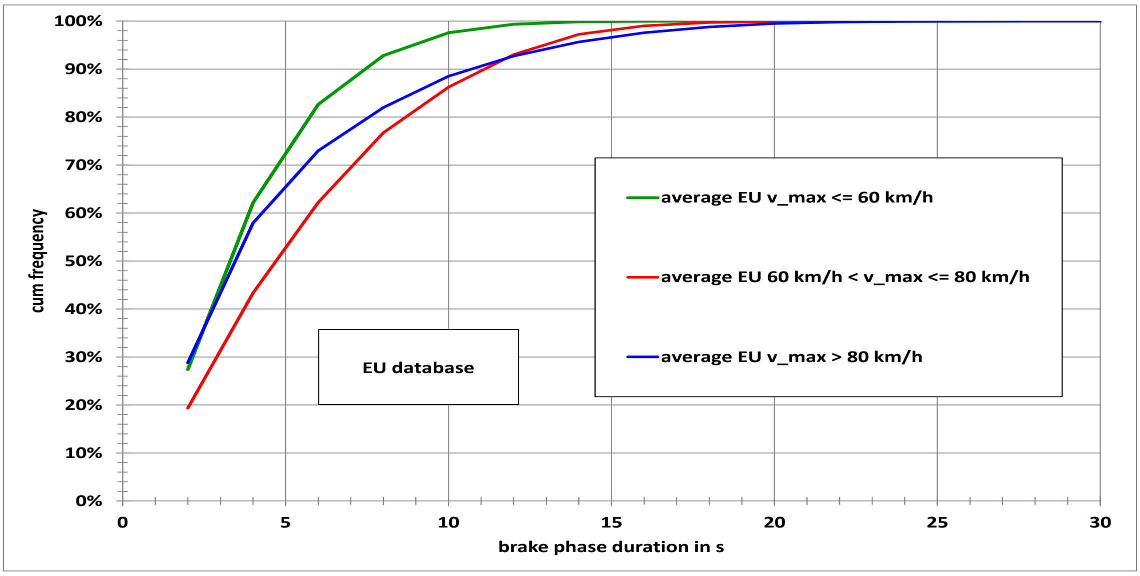


Figure 17: Brake phase duration distributions for short trips with different max speed

9.2.2 Brake phase distance distributions

Vehicle specific distance distributions for the different regions and for deceleration phases in short trips with max speed ≤ 60 km/h, between 60 and 80 km/h and > 80 km/h are given in Figure 18. Like in previous cases data for lower speeds exhibited homogeneity for different regions, while for higher speeds Asian data tend to differentiate from European and US data. In general, braking distances longer than 70 m are not very common (95th percentile) for urban areas worldwide. In highways the threshold value is between 200-250 m (Figure 18c).

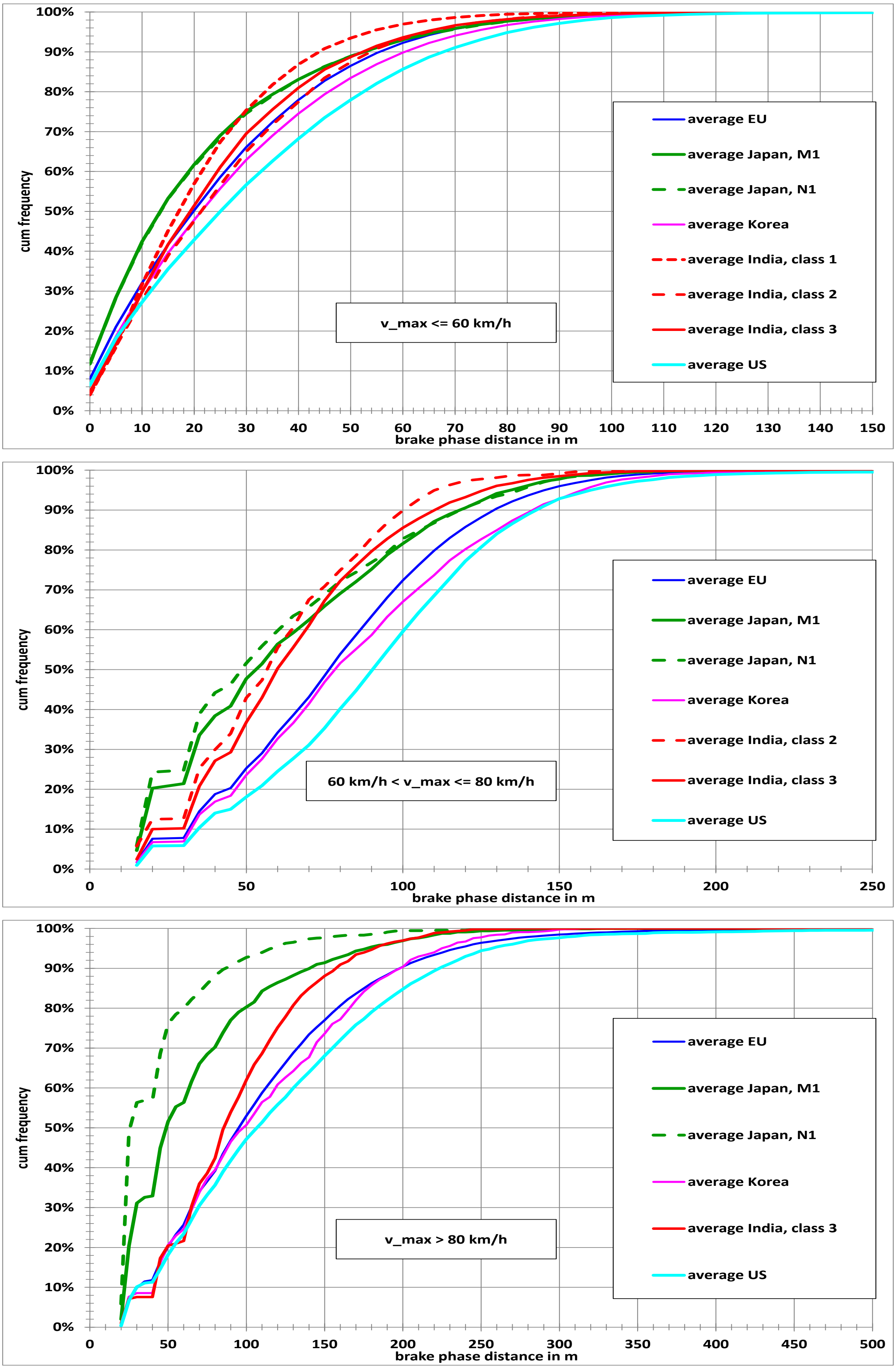


Figure 3: Brake phase distance distributions for the different regions and for different maximum speeds: a (max speed ≤ 60 km/h), b (60 km/h < max speed ≤ 80 km/h), c (max speed > 80 km/h)

Figure 19 shows a comparison of the average curves for the European data for short trips with different maximum speed ranges. The differences among speeds described for all regions are apparent. While median brake phase distance for the lower maximum speed category is 20 m it goes up to 100 m when the maximum speed category of > 80 km/h is examined. Also the "threshold" value of the brake phase distance rises from 70 m to 250 m when going from the lower to the higher maximum speed category.

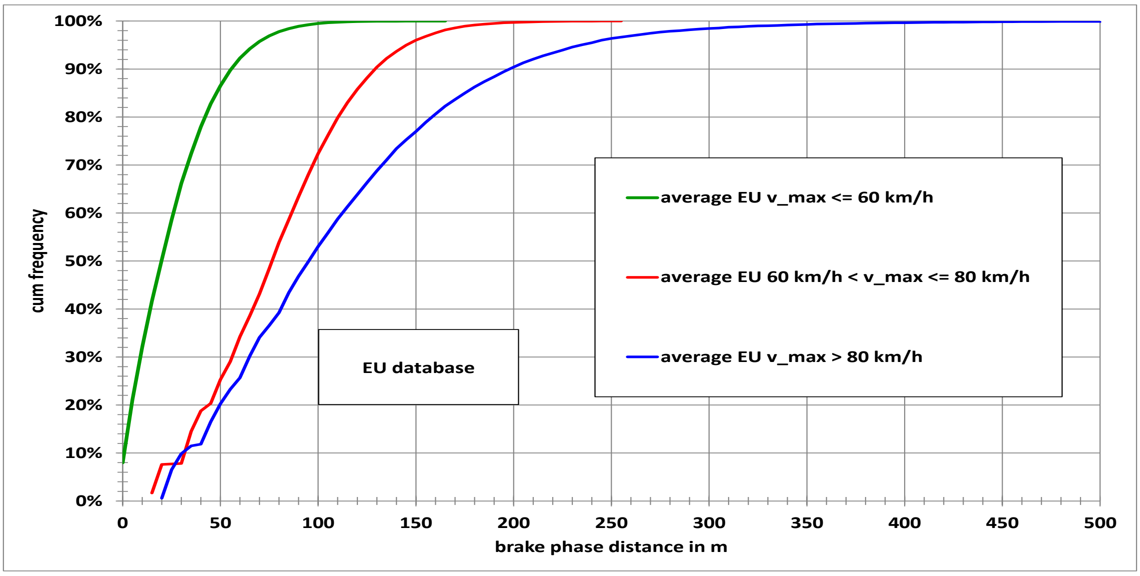


Figure 19: Brake phase distance distributions for short trips with different max speeds

9.2.3 Number of brake phases per km

Table 5 shows the number of brake phases per km distance driven for different regions, road categories and vehicles. From Table 5 it is seen that the average number of braking event per km in Europe, India and the US is approximately 1.5. Higher rates are observed in Korea and Japan. As discussed in a previous chapter almost 1 out of 5 trips in Europe and Japan occur within a creeping situation. This explains the high number of braking events (> 5 braking events/km) found in short trips with max speed of 60 km/h in these 2 regions.

Number of Braking Events per km [#/km]					
Region	Average	Short Trips with max Speed [km/h]			
		≤60	60 - 80	80 - 110	>110
Europe	1.56	5.3	2.1	1.0	0.4
India Class 1	1.36	1.7	0.5	0.0	0.0
India Class 2	1.55	3.7	1.3	0.8	0.0
India Class 3	1.84	4.4	1.9	1.1	1.1
Japan	3.00	6.1	2.1	0.7	0.4
Korea	2.01	4.3	1.5	0.8	0.7
USA	1.37	6.4	2.4	1.3	0.3

Table 5: Number of brake phases per km distance for different regions

Table 6 shows the number of brake phases per km for different regions per road category. In parenthesis where available the percentage of brake phases down to a stop phase with respect to the total number of brake phases is given. Unfortunately, US data came without information regarding the road type, therefore it was not possible to make the calculations.

Number of Braking Events per km [#/km]				
Region	Average	Type of Road		
		Urban	Rural	Motorway
Europe	1.56	3.8 (31.8%)	1.0 (15.7%)	0.2 (13.5%)
India Class 1	1.36	3.2	1.6	0.0
India Class 2	1.55	2.3	1.5	0.8
India Class 3	1.84	2.8	2.1	1.0
Japan	3.00	4.5 (34.5%)	1.3 (38.6%)	1.2 (22.7%)
Korea	2.01	3.6 (42.4%)	1.4 (19.5%)	0.7 (15.9%)
USA	1.37	*	*	*

Table 6: Number of brake phases per km (#) and percentage (%) of brake phases down to a stop phase with respect to the total number of brakes for different regions per road category

Table 6 shows that almost 4 braking events per vehicle per km occur in European urban areas. The average number of braking events per km is higher only in Japan. Almost 1 out of 3 braking events in European urban areas are down to stop phase (31.8%) with the major part of it being linked to creeping situations. Significantly lower braking rates are observed for rural areas and motorways. Generally higher braking rates both in terms of number of events and percentage of brake phases down to a stop phase are observed in Japan. It seems that the braking behaviour in Japan is different compared to the rest of the world. It is also noteworthy that 1.2 braking events per km occur in Japanese motorways with almost 20% of these events leading to the immobilization of the vehicle.

10 Acceleration distributions for accelerations > 0.15 m/s²

Figure 20 shows the acceleration distributions for different road categories in Europe (time weighted). Unfortunately these data are not available averaged for other regions worldwide (Asia, USA). However, details regarding other regions can be found in the detailed version of the current report.

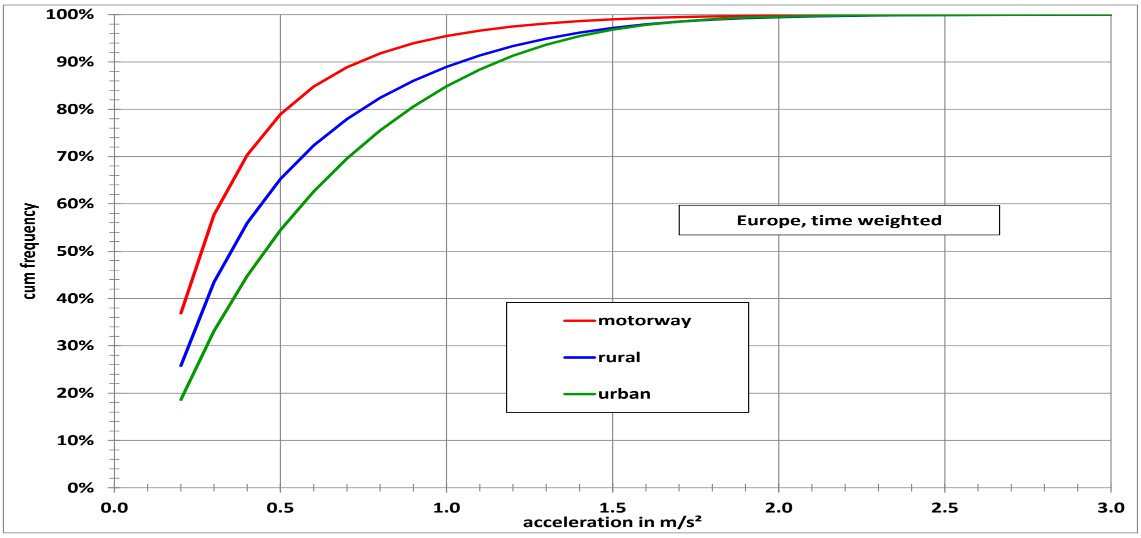


Figure 20: Acceleration distributions for road categories in Europe

It is seen from Figure 20 that median accelerations (50^{th} percentile) in European urban areas are close to 0.5 m/s^2, while lower values are observed in rural areas and motorways. In urban situations there are plenty of decelerations down to standstill at low speeds with high negative values, while decelerations on motorways are typically related to high vehicle speeds but lower decelerations on average. On the other hand, when investigating "threshold" values (95^{th} percentile) it is observed that accelerations higher than 1.4 m/s^2 can be characterized as **"extreme"**. Finally, it comes out that accelerations higher than 2.0 m/s^2 are very rare in European roads.

11 Deceleration distributions for decelerations < -0.15 m/s²

Figure 21 depicts the deceleration distributions for different road categories in Europe. Again this kind of data is not available averaged for other regions worldwide.

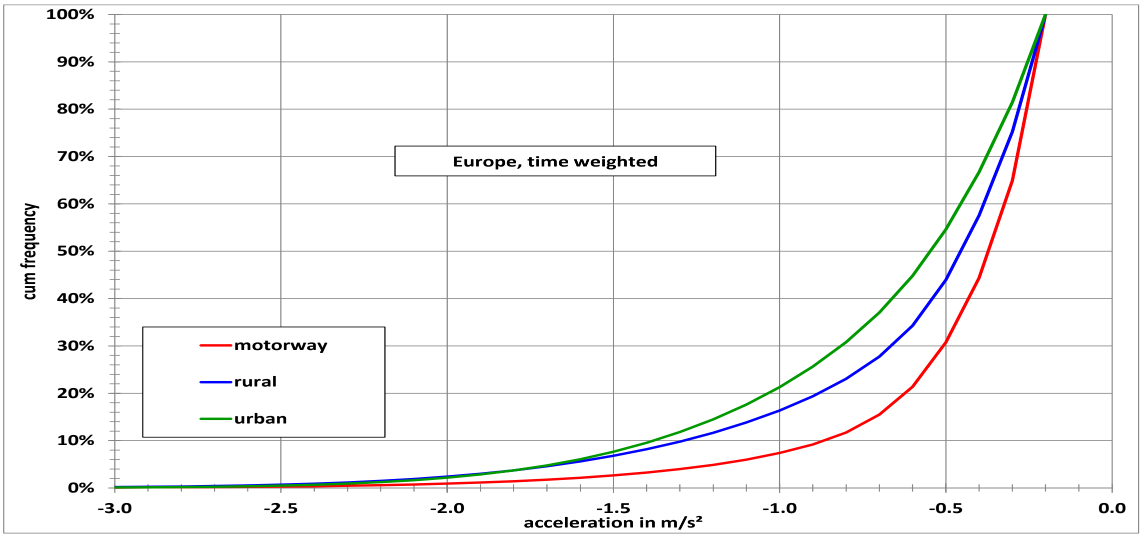


Figure 21: Deceleration distributions for road categories in Europe

It is seen from Figure 21 that median decelerations (50^{th} percentile) in European urban areas are close to -0.55 m/s^2, while lower values are observed in rural areas and motorways (approximately -0.4 m/s^2). "Threshold" values (95^{th} percentile) for decelerations in urban and rural areas are close to -1.7 m/s^2 and can be characterized as **"extreme"**.

12 v*a negative distributions for v*a < -1 m²/s³

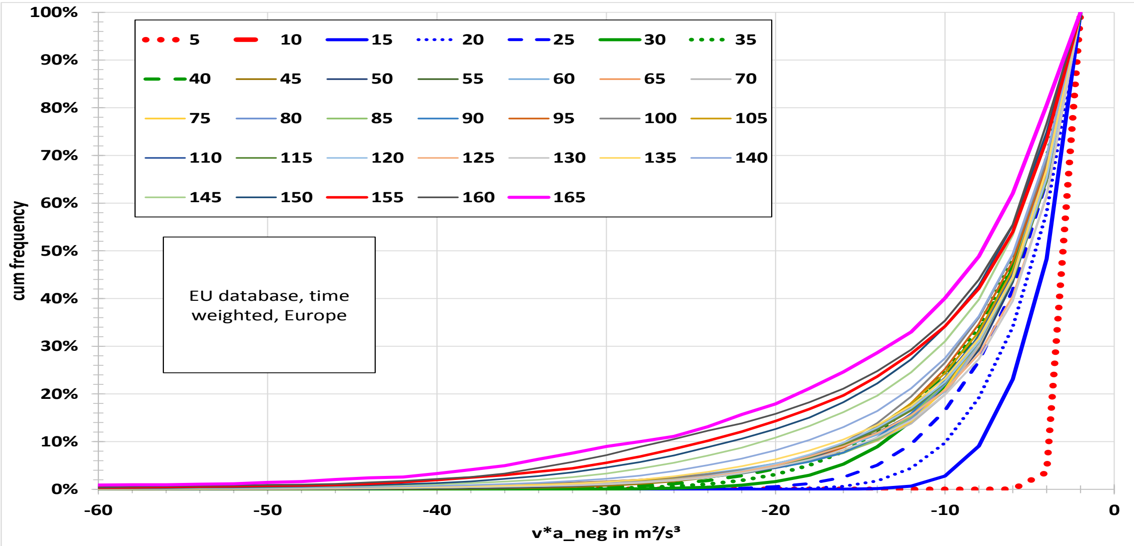
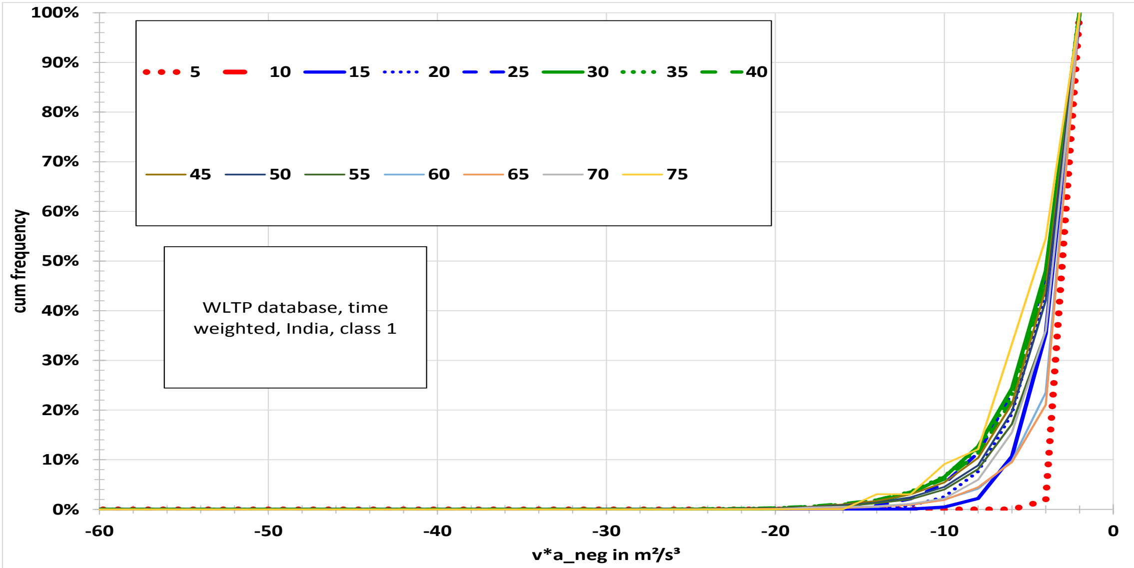
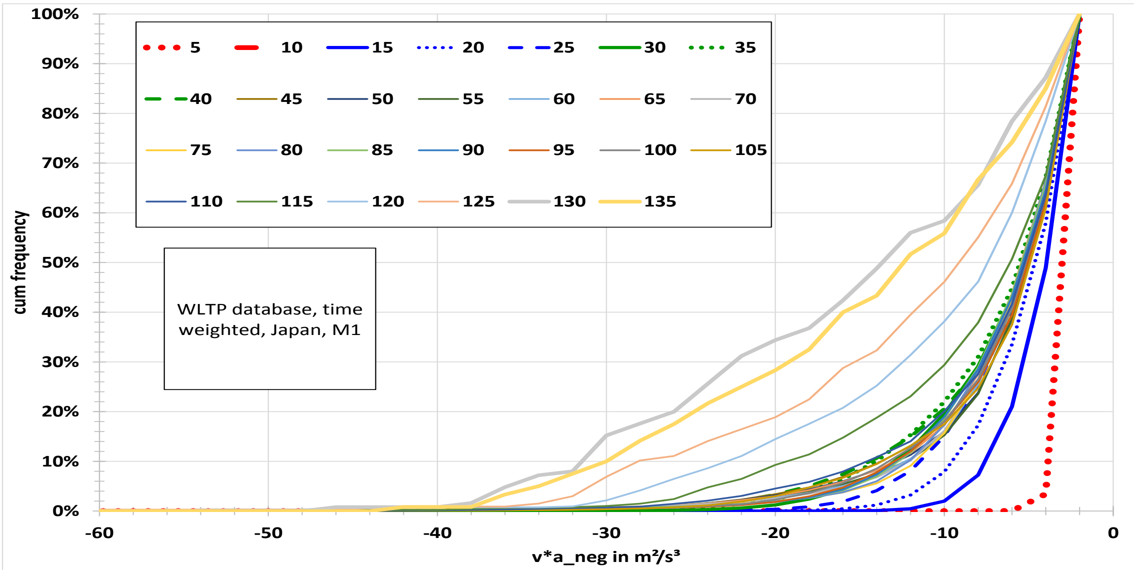


*Figure 22a: v*a distributions for vehicle speed classes in Europe*





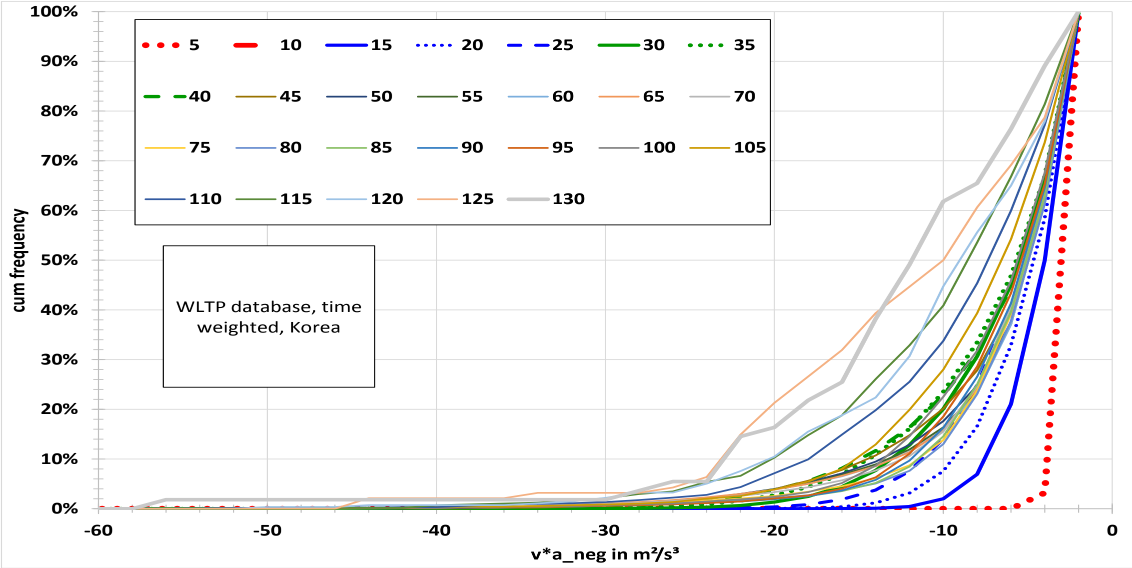


*Figure 22b-d: v*a negative distributions for vehicle speed classes: b (India class 1), c (Japan M1), d (Korea)*

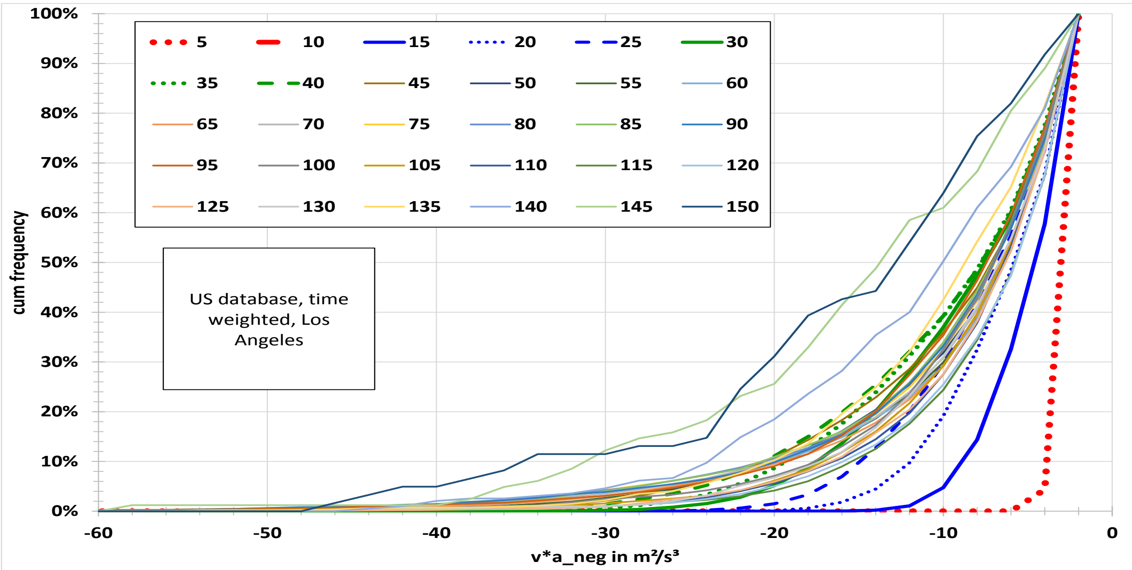


*Figure 22e: v*a negative distributions for vehicle speed classes in USA, Los Angeles*

Figure 22 depicts the vehicle speed*deceleration distributions for different maximum speed categories worldwide. These distributions are considered to be indicative for the energy dissipated in the wheel due to a braking event. Median values (50^{th} percentile) in the European region range from 3-8 m^2/s^3 depending on the speed category examined (2.8 m^2/s^3 is the averaged value for urban areas). In general, higher maximum speeds result in higher v*a values. Lower average values were observed in India (average values of 1.8-2.5 m^2/s^3 depending on the road category), while Korean, Japanese and US data exhibited a significantly wider range of values (3-15 m^2/s^3). On the other hand, threshold values for the European dataset range from 4-35 m^2/s^3 depending again on the speed category. Threshold values in the US were in some cases as high as 45 m^2/s^3.

Table 7 summarizes all the information described in the previous paragraph regarding the v*a negative distributions for different road categories worldwide. The US data could not be included in this particular part of the analysis because the available data do not allow the split into different road categories (i.e. urban, rural, motorway).

Region	Road Type	Cumulative Frequency						
		5%	10%	25%	50%	75%	90%	95%
Europe	Motorway	2.3	2.7	3.2	5.2	9.4	15.0	19.6
	Rural	1.1	1.5	2.3	4.4	7.9	12.7	16.7
	Urban	0.4	0.7	1.3	2.8	5.5	8.8	11.2
India	Motorway	0.7	1.0	1.6	2.5	4.9	8.1	10.6
	Rural	0.4	0.7	1.2	2.2	4.3	7.2	9.7
	Urban	0.2	0.4	0.8	1.8	3.7	6.4	8.4
Japan	Motorway	0.3	0.7	1.8	2.9	5.7	9.2	11.7
	Rural	1.0	1.2	1.5	2.7	4.8	7.5	9.2
	Urban	0.5	0.9	1.5	3.0	5.4	8.1	9.9
Korea	Motorway	0.2	0.5	1.3	2.4	4.6	7.2	9.2
	Rural	1.0	1.3	1.9	3.6	6.0	8.6	10.6
	Urban	0.4	0.7	1.3	2.8	4.9	7.0	8.5

Table 7: Vehicle speed*deceleration distributions for different regions worldwide per road category

13 Definition of a typical "journey" in the European region

Figure 23 shows the distribution of the number of short trips driven within a **"journey"** for different road categories in Europe. The distribution given as averaged refers to the number of stops within the **"journey"**. As a **"journey"** it is defined the distance and the stop phases from the moment the driver sets the engine on to the moment the vehicle is being parked. These distributions could give some information regarding the conditions under which a typical European journey is executed, meaning how many times the driver has to stop the vehicle due to traffic lights, traffic jams, etc.

Median number of stops within a European Journey (50^{th} percentile) was found to be somewhat more than 4. These stops occur within an average covered distance of approximately 13.2 km. On the other hand, the 95^{th} percentile for the number of stops is 15. It is characteristics that only very few "journeys" include more than 25 stops.

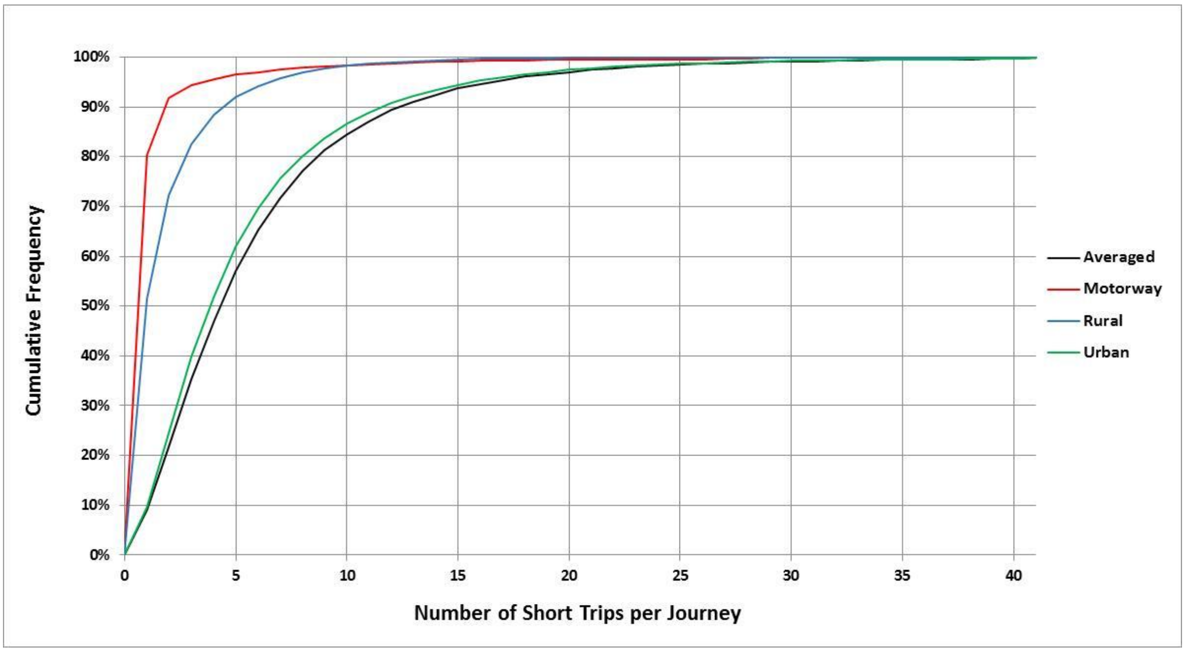


Figure 23: Distribution of the number of short trips per "journey" for different road categories in Europe. The distribution marked as averaged refers to the number of stops within the "journey"

When the median number of short trips within a "journey" (50th percentile) is examined there are significant differences among the 3 road categories. Average number of short trips in urban conditions is approximately 3.5, while in rural areas and motorways is almost 1. In urban areas the 3.5 stops occur within an average covered distance of approximately 3.7 km. On the other hand, the 95th percentile for the number of short trips in urban areas is 15. Lower values are recorded in rural areas and motorways (7 and 3 short trips in 56 and 15 km, respectively).

14 Conclusions

Driving conditions have a large influence on particle generation from brake and tyre wear processes. From the survey of the available literature it appears that different driving conditions in experimental investigation of particle emissions from brake and tyre wear is one of the reasons why different - or even sometimes- contradictory conclusions are reported.

In order to harmonize future studies on particles from brake and tyre wear and improve the comparability of the relative results, the definition of "normal" or "typical" driving patterns has been identified by PMP group as an important working item. The approach involved the use of activity data collected in the framework of other projects in order to investigate typical acceleration / deceleration frequency distributions. This report described the results of a detailed analysis of the WLTP in-use database. The main results for European Urban areas are summarized in the following Table 8. These results can be used at a later stage in order to build a respective braking cycle.

Europe	Cum Frequency	Vehicle Speed [km/h]	Acceleration [m/s^2]	Deceleration Duration [s]	Deceleration [m/s^2]	Stop Duration [s]	Short Trip Distance [m]	Brake Phase Duration [s]
urban	**5%**	1.7	≤0.20	≤2.0	≤0.20	≤2.0	≤50	1.0
	10%	4.6	≤0.20	≤2.0	0.25	≤2.0	≤50	1.0
	25%	14.0	0.25	2.6	0.33	2.3	69	1.9
	50%	28.3	0.45	4.7	0.55	5.8	264	3.3
	75%	42.4	0.79	7.8	0.91	18.5	782	5.2
	90%	53.6	1.16	11.7	1.40	38.6	1,818	7.5
	95%	60.2	1.35	14.5	1.70	55.0	3,270	9.0

Table 8: Distributions of parameters related to non-exhaust emissions in European Urban areas

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Figure 23: Distribution of the number of short trips per "journey" for different road categories in Europe. The distribution marked as averaged refers to the number of stops within the "journey"

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Annexes

Annex 1. Technical data of vehicles

Technical data of the vehicles used in the framework of the WLTP database in different regions worldwide are given in Table A1 to Table A4.

source	campagn	IDveh	engine	cap	Pn	kerb mass	GVM	n_rated	n_idle	category	Transmission type	number of gears
				cm³	kW	kg	kg	min-1	min-1			
Belgium	1	1	diesel	2188	85.0	1660	2180	4000	850	M1	manual	6
Belgium	1	2	diesel	1896	50.0	1121	1621	4000	900	M1	manual	5
Belgium	1	3	diesel	1896	77.0	1320	1800	4000	750	M1	manual	5
Belgium	1	4	diesel	2698	132.0	1600	2100	4250	750	M1	automatic	
Belgium	1	5	diesel	1398	50.0	960	1360	4000	750	M1	manual	5
Belgium	1	6	diesel	1998	85.0	1431	1900	4000	750	M1	manual	5
Belgium	1	7	diesel	1997	66.0	1125	1600	4000	800	M1	manual	5
Belgium	1	8	Petrol	1360	55.0	925	1325	5500	750	M1	manual	5
Belgium	1	9	diesel	1997	66.0	1423	1970	4000	850	M1	manual	5
Belgium	1	10	Petrol	1149	55.0	1090	1540	5000	750	M1	manual	5
Belgium	1	11	diesel	2231	130.0	1585	2100	3600	850	M1	manual	6
Belgium	2	3	diesel	2400	120.0	1851	2505	4000	750	M1	manual	6
Belgium	2	4	diesel	1560	80.0	1045	1513	4000	800	M1	manual	5
Belgium	2	5	diesel	1560	80.0	1560	2040	4000	800	M1	manual	5
Belgium	2	6	diesel	1560	80.0	1560	2040	4000	800	M1	automatic	6
Belgium	2	7	diesel	1600	80.0	1357	1875	4000	800	M1	manual	5
Belgium	2	8	diesel	1461	81.0	1290	1779	4000	850	M1	manual	6
Belgium	2	11	diesel	1461	81.0	1290	1779	4000	850	M1	manual	6
Belgium	2	15	diesel	1896	77.0	1473	1980	4400	750	M1	manual	5
Belgium	2	16	Petrol hybrid	1798	73.0	1495	1805	5200	900	M1	CVT	
Belgium	2	17	Petrol hybrid	1400	73.0	1495	1805	5200	900	M1	CVT	
Belgium	2	18	diesel	1422	59.0	1150	1590	4200	900	M1	manual	5
France	1	1	Diesel	1868	51.0	1023	1423	4600	950	M1	Manual	5
France	1	2	Petrol	1361	55.0	860	1260	5500	950	M1	Manual	5
France	1	3	Petrol	1361	55.0	860	1260	5500	850	M1	Manual	5
France	1	4	Petrol	1124	44.0	825	1225	6200	850	M1	Manual	5
France	1	5	Petrol	1360	55.0	860	1360	5500	900	M1	Manual	5
France	1	6	Petrol	1762	66.0	1170	1670	5500	800	M1	Manual	5
France	1	7	Petrol	1997	100.0	1595	2075	6000	700	M1	Manual	5
France	1	8	Diesel	1997	66.0	1300	1880	4000	800	M1	Manual	5
France	1	9	Petrol	2946	152.0	1520	2070	6000	850	M1	Automatic	4
France	1	10	Diesel	1997	80.0	1485	2100	4000	800	M1	Manual	5
France	2	11	Diesel	1560	80.0	1235	1715	4000	800	M1	Manual	5
France	2	12	Diesel	1997	100.0	1410	1890	4000	800	M1	Manual	6
France	2	13	Diesel	1530	80.0	1560	2040	4000	800	M1	Automatic	6
France	2	14	Diesel	1530	80.0	1560	2040	4000	800	M1	Automatic	6
France	2	15	Diesel	2721	150.0	1725	2275	4000	700	M1	Automatic	6
France	2	16	Diesel	1530	80.0	1560	2040	4000	800	M1	Automatic	6
France	2	17	Diesel	1997	100.0	1505	1985	4000	750	M1	Manual	6
France	2	18	Petrol	1587	80.0	1145	1606	5750	750	M1	Manual	5
France	2	19	Petrol	1997	103.0	1240	1970	6000	700	M1	Manual	5
France	2	20	Diesel	1997	100.0	1505	2005	4000	800	M1	Manual	6
France	2	21	Petrol	1360	65.0	1045	1513	5250	750	M1	Manual	5
France	2	22	Diesel	1997	100.0	1380	1860	4000	750	M1	Manual	6
France	2	23	Diesel	1560	80.0	1235	1970	4000	800	M1	Manual	5
France	2	24	Petrol	1360	65.0	1045	1513	5250	800	M1	Manual	5
France	2	25	Diesel	1560	80.0	1235	1970	4000	800	M1	Manual	5
France	2	26	Petrol	1587	80.0	1145	1606	5750	800	M1	Manual	5
France	2	27	Diesel	1997	100.0	1505	2005	4000	800	M1	Manual	6
France	2	28	Petrol	1360	65.0	1045	1513	5250	800	M1	Manual	5
France	2	29	Petrol	1587	80.0	1145	1606	5750	800	M1	Manual	5
France	2	30	Diesel	1997	100.0	1505	2005	4000	800	M1	Manual	6
France	2	31	Petrol	1360	65.0	1045	1513	5250	800	M1	Manual	5
France	2	32	Petrol	1360	65.0	1045	1513	5250	800	M1	Manual	5
France	2	33	Petrol	1587	80.0	1145	1606	5750	750	M1	Manual	5
France	2	34	Diesel	1560	80.0	1235	1970	4000	800	M1	Manual	5
France	2	35	Diesel	1560	80.0	1125	1593	4000	750	M1	Manual	5
France	2	36	Diesel	1560	80.0	1125	1593	4000	800	M1	Manual	5
France	2	37	Petrol	1997	103.0	1240	1970	6000	750	M1	Manual	5
France	2	38	Diesel	1560	80.0	1125	1593	4000	800	M1	Manual	5
France	2	39	Petrol	1997	103.0	1240	1970	6000	800	M1	Manual	5
France	2	40	Diesel	1560	80.0	1125	1593	4000	800	M1	Manual	5
France	2	41	Diesel	1560	80.0	1125	1593	4000	800	M1	Manual	5
France	2	42	Diesel	1560	80.0	1125	1593	4000	750	M1	Manual	5

Table A1: Technical data of the vehicles measured in Belgium and France

source	campagn	IDveh	engine	cap cm³	Pn kW	kerb mass kg	GVM kg	n_rated min-1	n_idle min-1	category	Transmission type	number of gears
Germany	1	3	DIESEL	2993	200.0	1635	2115	4000	700	M1	manual	6
Germany	1	5	Petrol	1300	70.0	945	1450	5250	750	M1	Manual	5
Germany	1	6	Petrol	998	50.0	775	1140	6000	850	M1	Manual	5
Germany	1	7	DIESEL	1560	66.0	1180	1580	4000	800	M1	Manual	5
Germany	1	13	Petrol	1998	100.0	1177	1580	6000	700	M1	Manual	5
Germany	1	14	Petrol	1598	64.0	1250	1890	5400	800	M1	Manual	5
Germany	1	15	DIESEL	1896	77.0	1452	2030	4000	850	M1	Manual	5
Germany	1	16	DIESEL	1364	55.0	905	1255	4000	800	M1	manual	5
Sweden	1	1	Diesel	2400	129.0	1690	2190	4000	700	M1	Automatic	5
Sweden	1	2	Diesel	1560	80.0	1394	1850	4000	800	M1	Manual	5
Sweden	1	3	Petrol/Hybrid	1798	73.0	1495	1900	5200	1000	M1	CVT	
Sweden	1	4	Petrol	1999	107.0	1574	2050	6000	800	M1	Manual	5
Sweden	1	5	Diesel	1560	80.0	1394	1850	4000	800	M1	Manual	5
Sweden	1	6	Petrol/Hybrid	1798	73.0	1495	1900	5200	900	M1	CVT	
Sweden	1	8	Diesel	2685	115.0	1930	3500	3800	700	N1	Manual	5
Sweden	1	9	petrol	2685	115.0	1930	3500	5000	650	N1	Manual	5
Italy	1	1	DIESEL	2900	106.0	1978	2470	3800	850	M1	Manual	6
Italy	1	2	Petrol	1600	75.0	1205	1655	5600	750	M1	Manual	6
Italy	1	4	DIESEL	2497	100.0	2027	2550	4400	800	M1	Manual	5
Italy	1	8	DIESEL	1968	55.0	1227	1650	4200	850	M1	Manual	6
Italy	1	9	DIESEL	1896	77.0	1335	1755	4000	850	M1	Manual	6
Italy	1	10	DIESEL	2148	125.0	1530	2000	3800	800	M1	Manual	5
Italy	1	11	DIESEL	1968	55.0	1227	1650	4200	800	M1	Manual	6
Italy	1	12	DIESEL	1422	51.0	1103	1530	4000	900	M1	Manual	5
Slovenia	1	18	Petrol	1400	55.0	1156	1575	5400	750	M1	Manual	5
Slovenia	1	20	Petrol	1598	78.0	1234	1720	5750	750	M1	Manual	5
Slovenia	1	21	DIESEL	2188	114.0	1968	2520	4000	800	M1	Automatic	5
Slovenia	1	22							750	M1		
Slovenia	1	23	Petrol	1598	83.0	1215	1720	6000	700	M1	Manual	5
Slovenia	1	24	DIESEL	1968	103.0	1454	1954	4000	800	M1	Manual	6
Slovenia	1	25	Petrol	1332	70.0	955	1355	6000	650	M1	Manual	5
Slovenia	1	26	Petrol	1149	55.0	1090	1490	5500	650	M1	Manual	5
Slovenia	1	27	DIESEL	1500	85.0	1255	1715	3750	850	M1	Manual	5
Slovenia	1	28	DIESEL	1800	66.0	1280	1750	3800	900	M1	Manual	5
Slovenia	1	29	Petrol	1596	74.0	1226	1750	5500	750	M1	Manual	5
Slovenia	1	30	DIESEL	1995	74.0	1560	2000	4300	900	M1	Manual	5
Slovenia	1	31	DIESEL	1995	130.0	1435	1915	4000	850	M1	Manual	6
Slovenia	1	32	DIESEL	2200	114.0	1502	1900	3500	800	M1	Manual	6
Slovenia	1	33	DIESEL	1896	95.0	1396	1900	4000	850	M1	Manual	6
Slovenia	1	34	DIESEL	1461	60.0	1205	1650	4000	800	M1	Manual	5
Slovenia	1	35	DIESEL	1910	89.0	1568	2000	3500	800	M1	Manual	6

Table A2: Technical data of the vehicles measured in Germany, Sweden, Italy and Slovenia

source	campagn	IDveh	engine	cap	Pn	kerb mass	GVM	n_rated	n_idle	category	Transmission	number
				cm³	kW	kg	kg	min-1	min-1		type	of gears
UK	1	1	Diesel	2200	63.0	1580	2600	3500	800	N1	Manual	5
UK	1	2	Diesel	2198	62.0	1800	2800	3500	800	N1	Manual	5
UK	1	3	Diesel	2200	63.0	1580	2600	3500	800	N1	Manual	5
UK	1	4	Diesel	2200	63.0	1580	2600	3500	800	N1	Manual	6
UK	1	5	Diesel	2200	63.0	1580	2600	3500	800	N1	Manual	5
UK	1	6	Diesel	2000	84.0	1877	2900	3500	800	N1	Manual	6
UK	1	7	Diesel	2148	80.0	2015	3500	3800	850	N1	Manual	6
UK	1	8	Diesel	2148	80.0	2180	3500	3800	850	N1	Automatic	5
UK	1	9	Diesel	2148	80.0	2180	3500	3800	850	N1	Automatic	5
UK	1	10	Diesel	2400	84.0	2034	3600	3500	800	N1	Manual	6
UK	1	11	Diesel	2400	84.0	2034	3600	3500	800	N1	Manual	6
UK	1	12	Diesel	1750	55.0	1415	2040	4000	850	N1	Manual	5
UK	2	1	DIESEL	3000	202.0	1820	2275	4000	700	M1	automatic	6
UK	2	2	Petrol	1108	40.0	840	1255	5000	750	M1	Manual	5
UK	2	3	Petrol	1798	88.0	1391	1920	6000	800	M1	Manual	5
UK	2	4	Diesel	1870	80.0	1350	1940	4000	800	M1	Manual	6
UK	2	5	Petrol	2522	165.0	1392	1843	6000	800	M1	Manual	6
UK	2	6	DIESEL	1997	85.0	1557	2070	3750	800	M1	Manual	6
UK	2	7	Petrol	1242	80.0	966	1415	5800	750	M1	Manual	5
UK	2	8	Diesel	1753	85.0	1391	1848	3800	900	M1	Manual	5
UK	2	9	Petrol	1596	74.0	1255	1721	6000	750	M1	Automatic	4
UK	2	10	DIESEL	1995	110.0	1525	1970	4000	850	M1	manual	6
Poland	1	1	DIESEL	1248	66.0	1310	1768	4000	800	M1	Manual	6
Poland	1	2	Petrol	1362	66.0	1155	1613	5600	800	M1	Manual	5
Poland	1	3	DIESEL	1896	66.0	1270	1780	4000	900	M1	Manual	5
Poland	1	4	DIESEL	1560	80.0	1489	2040	4000	800	M1	Manual	5
Poland	1	5	Petrol	998	50.0	865	1180	6000	850	M1	Manual	5
Poland	1	6	Diesel	1910	84.0	1410	1845	4000	850	M1	Manual	5
Poland	1	7	Petrol	1598	81.0	1055	1550	6000	700	M1	Manual	5
Poland	1	8	Diesel	2494	86.0	1750	2800	3600	700	N1	Manual	5
Poland	1	9	Petrol	1149	55.0	950	1345	5500	750	M1	Manual	5
Spain	1	1	DIESEL	1896	77.0	1125	1591	4000	850	M1	Manual	5
Spain	1	2	Petrol	1364	103.0	920	1378	4900	800	M1	Manual	6
Spain	1	3	Diesel	1995	105.0	1385	1810	4000	850	M1	Manual	6
Spain	1	5	Petrol	1390	92.0	1403	1970	5000	700	M1	Manual	6
Spain	1	6	Diesel	1560	80.0	1344	1970	4000	750	M1	Manual	5
Spain	1	7	Diesel	1560	66.0	1504	2065	4000	750	N1	Manual	5
Spain	1	8	DIESEL	2402	85.0	2034	3500	3500	800	N1	Manual	6
Spain	1	9	DIESEL	1753	55.0	1392	1955	4000	850	N1	Manual	5
Spain	1	10	DIESEL	2402	85.0	1865	3500	3500	800	N1	Manual	6

Table A3: Technical data of the vehicles measured in UK, Poland and Spain

source	campagn	IDveh	engine	cap	Pn	kerb_mass	GVM	n_rated	n_idle	category	Transmission type	number of gears
				cm³	kW	kg	kg	min-1	min-1			
USA	1	1801	Petrol	4511	250.0	2225	2880	6500	550	M1	automatic	6
USA	1	1802	Petrol	3189	184.0	2170	2880	6300	700	M1	automatic	6
USA	1	1803	Petrol	4511	250.0	2225	2880	6500	550	M1	automatic	6
USA	1	1804	Petrol	4511	331.0	2355	2880	6000	550	M1	automatic	6
USA	1	1805	Petrol	3189	184.0	2160	2880	6300	700	M1	manual	6
Japan	1	1	Petrol	1490	75.0	1040	1315	5600	700	M1	Automatic	4
Japan	1	2	Petrol	990	51.0	860	1135	8000	700	M1	Automatic	4
Japan	1	3	Petrol	2350	121.0	1560	1945	7500	600	M1	Automatic	4
Japan	1	4	Petrol	1339	73.0	1140	1415	6000	750	M1	Automatic	5
Japan	1	5	Diesel	2980	96.0	2050	2490	3600	700	M1	Automatic	4
Japan	1	6	Diesel	2950	125.0	2210	2595	3600	750	M1	Automatic	4
Japan	1	7	Petrol	1496	81.0	1020	1295	6000	650	M1	Manual	5
Japan	1	8	Petrol	658	40.0	700	920	6500	800	M1	Manual	5
Japan	1	9	Petrol	997	51.0	840	1115	6000	750	M1	Manual	5
Japan	1	10	Petrol	1998	116.0	1440	1715	6500	650	M1	Manual	5
Japan	1	11	Petrol	1998	162.0	1180	1400	8000	750	M1	Manual	6
Japan	1	12	Petrol	660	32.0	920	1380	5900	900	N1	Automatic	3
Japan	1	13	Petrol	1790	66.0	1310	2225	5000	700	N1	Automatic	4
Japan	1	14	Petrol	1990	81.0	1580	2995	5200	850	N1	Automatic	4
Japan	1	15	Diesel	2180	58.0	1380	2295	4250	650	N1	Automatic	4
Japan	1	16	Diesel	2990	67.0	1700	3115	4000	650	N1	Automatic	4
Japan	1	17	Diesel	2980	100.0	1920	2850	3400	800	N1	Automatic	4
Japan	1	18	Petrol	650	31.0	800	1260	5500	1050	N1	Manual	5
Japan	1	19	Petrol	1990	88.0	1550	2965	5200	700	N1	Manual	5
Japan	1	20	Petrol	657	37.0	880	1340	6000	900	N1	Manual	5
Japan	1	21	Petrol	1789	66.0	1210	2225	5000	750	N1	Manual	5
Japan	1	22	Diesel	2180	57.0	1350	2265	4250	700	N1	Manual	5
Japan	1	23	Diesel	1998	54.0	1160	1570	4500	750	N1	Manual	5
Japan	1	24	Diesel	2835	69.0	1790	3455	4000	800	N1	Manual	5
Korea	1	1	Petrol	1591	121.0	1545	2025	6200	650	M1	Automatic	
Korea	1	2	Petrol	1998	165.0	1735	2235	6200	600	M1	Automatic	
Korea	1	3	Petrol	2656	192.0	1960	2460	6000	650	M1	Automatic	
Korea	1	4	Diesel	1991	151.0	2345	2900	3800	800	M1	Automatic	
Korea	1	5	Diesel	2902	192.0	2945	3500	3800	800	N1	Automatic	
Korea	1	6	Diesel	2497	174.0	3035	3500	3800	800	N1	Automatic	
Korea	1	7	Diesel	2497	126.0	1955	2800	3800	750	N1	Automatic	
Korea	1	8	Diesel	2497	126.0	1950	2800	3800	750	N1	Manual	5
India	1	1	Diesel	2498	83.2	1830	2475	3800	750	M1	manual	5
India	1	2	Diesel	442	6.8	670	1250	3600	1000	N1	manual	4
India	1	3	Petrol	624	26.0	635	935	5500	1150	M1	manual	4
India	1	4	Diesel	2179	103.0	2225	2850	4000	850	M1	manual	5
India	1	5	Diesel	702	11.3	815	1550	3200	850	N1	manual	4
India	1	6	Petrol	1248	55.9	1130	1572	5150	850	M1	manual	5
India	1	7	CNG	796	35.0	795	1140	6200	900	M1	manual	5
India	1	8	Petrol	998	49.0	880	1320	6200	900	M1	manual	5
India	1	9	Diesel	2523	46.3	1725	2750	3200	850	N1	manual	5
India	2	10	DIESEL	1248	68.2	1210	1670	4000	850	M1	MANUAL	5
India	2	11	PETROL	1368	65.9	1180	1619	6000	850	M1	MANUAL	5
India	2	12	Petrol	1172	50.2	1090	1520	6000	850	M1	MANUAL	5
India	2	13	Petrol	1198	66.0	1055	1430	6200	750	M1	Manual	5
India	2	14	Petrol	1086	49.0	895	1360	5500	750	M1	Manual	5
India	2	15	Petrol	1197	58.8	1033	1515	5200	700	M1	Manual	5
India	2	16	DIESEL	1248	55.2	1080	1505	4000	900	M1	MANUAL	5
India	2	17	petrol	996	50.0	870	1275	6200	850	M1	Manual	5
India	2	18	Diesel	1500	65.0	1250	2500	3700	800	N1	Manual	5
India	2	19	PETROL	1496	66.0	930	1430	5600	850	M1	MANUAL	5
India	2	20	Diesel	1598	77.0	1220	1760	4400	800	M1	Manual	5
India	3	21	Diesel	2596	45.0	1700	2850	3600	800	N1	Manual	5
India	3	22	Diesel	1947	29.1	1350	2450	2900	850	N1	Manual	4
India	3	23	Diesel	2523	46.3	1725	2750	3200	850	N1	Manual	5
India	3	24	Diesel	2523	46.3	1670	2330	3200	900	M1	Manual	5
India	3	25	Diesel	442	6.8	670	1250	3600	1000	M1	Manual	4
India	3	26	Diesel	909	18.4	950	1800	4000	1050	N1	Manual	4
India	3	27	PETROL	796	25.0	785	1350	5000	900	M1	MANUAL	4
India	3	28	Diesel	441	6.5	597	1100	3600	1000	N1	Manual	4
India	3	29	Diesel	871	12.5	800	1810	3000	1250	N1	Manual	5
India	3	30	Diesel	702	11.3	815	1550	3200	850	N1	manual	4
India	3	31	Diesel	611	8.0	685	1110	3000	1100	M1	Manual	5

Table A4: Technical data of the vehicles measured in USA, Japan, Korea and India

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